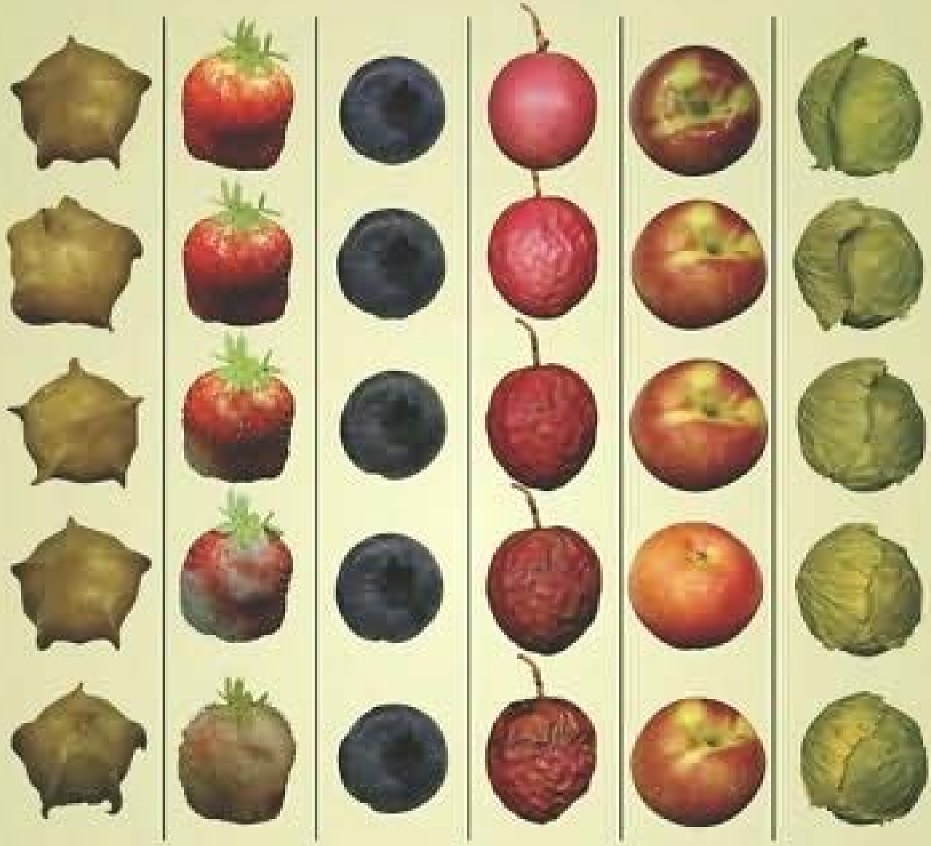
COLOR ATLAS OF POSTHARVEST

Quality *of* Fruits *and* Vegetables

Maria Cecília do Nascimento Nunes



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Dedicated to my husband, Jean-Pierre, and to my twin daughters, Sarah and Sofia. Without their love and devoted enthusiastic support this book would not have been completed.

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FOREWORD

Cecilia Nunes came to the University of Florida in 1992 to work on her Ph.D. dissertation research in strawberry postharvest physiology with Steve Sargent and me as part of a collaborative agreement with the College of Biotechnology (ESB), Catholic University of Portugal, Porto, Portugal. Cecilia ended up spending three consecutive Florida strawberry harvest seasons with us and I remember thinking at the time that she was one of the most organized and productive young scientists that I had ever encountered. Her Ph.D. research from those 3 years was wide ranging, including strawberry fruit development, postharvest temperature effects on strawberry quality (a theme being initiated, perhaps!), controlled atmosphere storage, and plant pathology.

In 1997, several years after Cecilia left Florida, I spent a sabbatical leave at University Laval in Quebec, Canada, with Jean-Pierre Emond, with whom Cecilia was working. At that time, Cecilia had begun a research project to develop "quality curves" for many of the most important fruit and vegetable crops in international commerce. Her idea was to document as many quality changes in a crop as possible (a dozen or more in some cases), measuring them during storage of replicated samples at a range of different temperatures encompassing those temperatures that may be encountered in the postharvest environment. It may seem surprising to some of you reading this, but this is something that has almost never been done for any crop over some 90 years of previous postharvest research! The reason for this seeming lack of effort is that, postharvest physiology being a practical discipline and subject to budgetary limitations like all other fields of science, previous postharvest storage research has almost always been directed toward answering more or less specific questions—such as "What is the optimum storage temperature for this crop?" or "What is the response of this crop to storage at a chilling temperature?"—rather than directed toward creating a picture of the total embodiment of quality that develops over time and over a wide range of temperatures, as Cecilia undertook to do.

From the start, Cecilia has envisioned the results of her quality curve research being applied to a modeling of the changes in quality that occur in all fruits and vegetables during their postharvest life, the idea being that a record of the previous temperature history of a particular lot of produce up to any point in its distribution could be used to predict its remaining postharvest life under any subsequent set of temperature conditions. Such a tool would be extremely useful to many people working in the food industry as well as to other scientists interested in how various quality parameters change and become limiting in terms of fruit and vegetable shelf life. Cecilia realized, however, that visual documentation of the effects of temperature on the products would be very valuable in applying this modeling concept. The meticulous work of setting and re-setting up the fruits and vegetables in exactly the same position and with exactly the same lighting and so forth on a daily basis for weeks at a time that was required to produce those images is an accomplishment not to be casually disregarded.

As Cecilia began to present her results in seminars and at scientific meetings, she also began to hear an oft-repeated statement: "You should collect all of this into a book!" The example often cited is Anna Snowden's two-volume *A Colour Atlas of Postharvest Diseases and Disorders of Fruit and Vegetables,* now out of print, which earned a place on the shelves of many people working in the field due to its usefulness as a resource for identifying and understanding the storage diseases of fruits and vegetables.

What you have in this book, *Color Atlas of Postharvest Quality of Fruits and Vegetables,* is the result of some 10 years of laboratory simulations of postharvest temperature exposure for some three dozen different fruit and vegetable crops. I am confident that you will be gratified by the effort expended by the author to create it and thankful to her for sharing her efforts with us. I trust that you will find this book to be a very useful and interesting reference for recognizing and understanding the important changes that take place in fruits and vegetables after harvest as a result of exposure to different temperatures.

Jeffrey K. Brecht, Ph.D.
Professor, Horticultural Sciences Department, and
Director, Center for Food Distribution & Retailing
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I would like to express my gratitude to all of those who contributed to this book. First to my dearest mentor, colleague, and friend, Jeffrey K. Brecht, from the Department of Horticultural Sciences at the University of Florida, who introduced me to the field of postharvest of fruits and vegetables, and who has always been there for me. His constant dedication, support, and enthusiasm guided me through my years as a graduate student and throughout the establishment of my career as a scientist. Jeffrey's contribution to this book was extremely valuable, and I have no words to express my sincere appreciation.

Second, I would like to acknowledge my first research assistant, Nadine Béland, who was an excellent partner during my first years as a scientist at the University Laval in Canada. Thanks to Nadine we were able to photograph many fruits and vegetables. I would also like to show my appreciation to students Sharon Dea, Emilie Proulx, Magalie Laniel, William Pelletier, and Emilie Laurin for their contributions to this project.

I am also very grateful to my dear colleague scientists who trusted my work and accepted my invitation to comment on the text, especially Charles F. Forney, from the Atlantic Food and Horticulture Research Centre, Agriculture and Agri-Food Canada; Penelope Perkins-Veazie, from the Agricultural Research Service, United States Department of Agriculture; and Donald J. Huber, Mark A. Ritenour, and Steven A. Sargent, from the Department of Horticultural Sciences at the University of Florida, for their wise and useful comments. I would also like to acknowledge Adel A. Kader, from the Department of Pomology at the University of California, who with his knowledgeable and positive review helped to promote this book. Also to my husband and colleague, Jean-Pierre Emond, from the Department of Agricultural and Biological Engineering at the University of Florida, a big thanks for his suggestions and, most of all, for his patience. To my brother Daniel, outstanding graphic designer, another big thanks for helping arrange the photographs in a more professional fashion. Finally, I acknowledge Envirotainer AB, Sweden, for sponsoring part of this project.

INTRODUCTION

Fresh fruits and vegetables are essential constituents of a healthy and well-balanced diet, as they *supply several biologically important components to the human organism.* Fruits and vegetables are the major source for the vitamin C and vitamin A required in the human diet (Block 1994; Lester 2006; Marston and Raper 1987). For example, depending on the age group, the daily requirement for vitamin C is about 60–90 mg (Ausman and Mayer 1999; DRI 2000), and many vegetable crops such as broccoli, red peppers, and strawberries contain this amount in about 100 g of fresh tissue (Lundergan and Moore 1975; McCance and Widdowson 1978; USDA 2006).

In addition, fruits and vegetables constitute a rich source of phytochemicals such as provitamin A carotenoids, as well as other carotenoids (i.e., lycopene and lutein), phenolic flavonoids, glucosinolates, and other bioactive components with potential anticarcinogenic and cardiovascular risk reduction properties (Ackermann et al. 2001; Burri 2002; Clinton 1998; Fleischauer and Arab 2001; Giovannucci 2002; Kaur and Kapoor 2001; McDermott 2000; Ness and Powles 1997; Steinmetz and Potter 1996; Veer et al. 2000; Verhoeven et al. 1997; Yang et al. 2001). Phytochemicals present in plants can act as reducing agents, free radical terminators, metal chelators, and singlet oxygen quenchers, as well as mediating the activity of various oxidizing enzymes (Ho 1992; Rice-Evans et al. 1997).

Bioactive food components contribute to the antioxidant capacity of fruits and vegetables by scavenging harmful free radicals, which are implicated in most degenerative diseases (Amagase et al. 2001; Ausman and Mayer 1999; Kaur and Kapoor 2001; Vinson et al. 2001; Wang et al. 1996; Yang et al. 2001). Levels of these bioactive compounds in fruits and vegetables can vary with genotype, maturity, and location within the plant tissue (Barrett and Anthon 2001; Brovelli 2006; Howard et al. 2000; Lee and Kader 2000; Lester 2006; Perkins-Veazie et al. 2002). In addition, phytochemical levels in plants may be influenced by growing conditions and by postharvest handling and environmental conditions (i.e., pre-cooling methods, storage temperatures, humidity and atmosphere composition, packaging, shipping methods) and by processing or cooking (Brecht et al. 2004; Brovelli 2006; Cisneros-Zevallos 2003; Howard et al. 1999; Hussein et al. 2000; Jones et al. 2006; Kalt 2005; Lee and Kader 2000; Lester 2006; Shi and Maguer 2000; Vallejo et al. 2002).

Postharvest environmental conditions, in particular *temperature,* have a major impact on the visual, compositional, and eating quality of fruits and vegetables. Temperature is, in fact, the component of the postharvest environment that has the greatest impact on the quality of fresh fruits and vegetables. Good temperature management is the most important and simplest procedure for delaying product deterioration. Optimum preservation of fruit and vegetable quality can only be achieved when the produce is promptly cooled to its optimum temperature as soon as possible after harvest. In general, the lower the storage temperatures within the limits acceptable for each type of commodity, the longer the storage life. For each horticultural commodity there is assumed to be an optimal postharvest storage temperature at which the rate of product deterioration is minimized. Storage of fruits and vegetables at their optimum temperature retards aging, softening, textural, and color changes, as well as slowing undesirable metabolic changes, moisture loss, and losses due to pathogen invasion. Many studies have demonstrated that maintenance of an optimum temperature from the field to the store is crucial for maintaining fruit and vegetable quality (Alvarez and Thorne 1981; Bourne 1982; King et al. 1988; Laurin et al. 2003; Nunes and Emond 2002; Nunes et al. 1995, 1998, 2003a, 2003b, 2004, 2005, 2006, 2007; Paull 1999; Proulx et al. 2005; Toivonen 1997; Van den Berg 1981).

Visual quality is one of the most important factors that determine the market value of fresh fruits and vegetables. When consumers were asked about how they choose fresh fruits and vegetables, ripeness, freshness, and taste were named by 96% as the most important selection criteria, while appearance and condition of the product came in second in order of importance (94%) (Zind 1989). Although not visually perceptible, nutritional value was considered by about 66% of the consumers to be the decisive factor for buying the product (Zind 1989). Color, for instance, is one of the major attributes of product appearance and is a primary indicator of maturity or ripeness. However, undesirable changes in the uniformity and intensity of color due to changes in pigments can be observed when fruits and vegetables are not stored at optimum temperatures. Temperature can therefore have a direct effect on color changes during storage of fresh fruits and vegetables. For example, while loss of chlorophyll is a desirable process in a few fruits and vegetables such as tomato, peach, mango, and some sweet pepper cultivars, yellowing of green vegetables such as broccoli or Brussels sprouts is considered undesirable.

Softening of fleshy tissues of some fruits and vegetables such as mango, tomato, cucumber, sweet pepper, and others is one of the most important changes occurring during storage and also has a major effect on consumer acceptability. Changes in the overall textural quality of vegetables include decreased crispness and juiciness or increased toughness. Crispness is expected in fresh apples, peaches, and green onions, but tenderness is desired in asparagus and green beans. In the particular case of leafy vegetables, as they lose water they can wilt, shrivel, and become flaccid, losing their expected attractive appearance.

The nutritional value of fruits and vegetables can also be greatly affected by storage temperature. In general, vitamin C degradation is very rapid after harvest and increases as the storage time and temperature increase. For example, Nunes et al. (1998) observed that losses in vitamin C content in several strawberry cultivars stored at 1°C ranged from 20 to 30% over 8 days, while fruit stored at 10°C lost from 30 to 50% of its initial vitamin C content. At 20°C, losses were very high and berries lost 55–70% of their initial vitamin C content in only 4 days.

In brief, even though fruits and vegetables bring to our daily food consumption diversity in color, texture, and flavor, as well as many nutritious and important bioactive compounds, if handled under improper conditions, a great part of these benefits may be significantly lost.

The *main purpose of this book* is to show by series of photographs how the *visual quality* of fruits and vegetables changes throughout their postharvest life and how *temperature* greatly contributes to critical quality changes. For that purpose, a total of thirty-five different fruits and vegetables from different categories were stored in the dark at temperatures ranging from 0 to 25°C and the same fruit or vegetable was photographed regularly (i.e., daily or every other day), always under the same conditions, during different periods of time, depending on the expected postharvest life of the fruit or vegetable at each particular temperature.

This book also gives the reader detailed information about each individual fruit or vegetable, such as characteristics, quality criteria, handling recommendations, effects of temperature on appearance, and compositional and eating quality, combined with pictures of the appearance of selected fruits and vegetables at a particular temperature and time. The pictures clearly show how different quality factors limit the postharvest life of each individual fruit or vegetable crop at different temperatures.

The pictures included in this book definitely show how important it is to handle fruits and vegetables at their optimum temperatures and what may happen if storage temperature recommendations are not followed. The book also shows the importance of the initial quality of the fruit or vegetable at harvest in determining its postharvest life as a function of storage time and temperature.

The photographs in this book show what happens to freshly harvested, best quality fruits and vegetables when held in a controlled environment. Since in real life things are different from controlled environments like our laboratories, some of the symptoms described in this book may develop earlier and in more severe ways when fruits and vegetables are handled under commercial conditions. For example, in this study, the relative humidity used was the optimum or close to the optimum recommended for each fruit and vegetable, which is definitely not a situation that we will normally find in commercial operations. In some cases, the effects of temperature alone that are documented in this book were quite severe. Thus, in real life situations (i.e., where the initial quality of the fruit or vegetable is not the best, delays between harvest and cooling are not minimized, humidity is not controlled, mechanical and physical aspects are not controlled) we can expect that, while the visual signs of quality loss will be similar to those presented in this book, those symptoms will likely develop earlier and more severely.

One might argue that the cultivars used in this book do not represent the main cultivars used worldwide. However, even if we could have the same exact fruit or vegetable cultivar grown in Europe, North America, South America, Africa, Asia, and Australasia, the variations in climate, soil, preharvest, and postharvest treatments, or even packaging materials, could easily influence the postharvest behavior of that cultivar so that it behaves in each location as if it were a completely different cultivar. While in some cases the cultivars we used were typical to the region of harvest (i.e., Florida or Quebec), in other cases the cultivars were "worldwide classics." For the purpose of this study it was extremely important to have the freshest, best quality fruits and vegetables available, and with known growing conditions. Therefore, the cultivars used were those that were easily available and from the closest distances to our laboratory, so the maximum time between harvest and beginning of the experiments was no more than 6 hours. Although we will always find differences in the behavior of different fruit or vegetable cultivars, or the same cultivars from different areas of the globe, in response to time-temperature conditions, through the information presented in this book the reader should be able to obtain a very good appreciation for how visual quality changes, independently of the cultivar used.

Academic and scientific professionals in the areas of postharvest physiology, postharvest technology, food science, and human nutrition may use this book as a reference, either for their own studies or in their classes, in order to help students visualize changes in the appearance of fruits and vegetables as a function of time and temperature. Food industry professionals involved in processing, distribution, retail, quality control, packaging, temperature control (i.e., refrigerated facilities or equipment), or marketing may use this book as a reference tool or to establish marketing priority criteria. For example, a quality control individual, responsible for accepting or rejecting a load of produce at a distribution center, may be able to identity the average quality of the load (i.e., excellent–poor) based on the pictures shown in this book; a decision can be made, based on the visual appearance and estimated remaining postharvest life, as to whether the load should be sent immediately to the retail store or if it may be kept some additional days at the distribution center. In addition, professionals in the area of temperature control (i.e., pre-cooling systems, cold rooms, refrigerated trailers, and refrigerated consumer displays) may use this book to show their clients how important it is to control and maintain the right temperature during storage, transport, or retail display of fresh fruits and vegetables.

This book is organized in eight major chapters, and again the goal of each chapter is to show the importance of proper temperature management. Chapters 1 through 8 describe first the most important quality criteria when selecting each particular fruit or vegetable, handling and storage recommendations (i.e., optimum temperature and relative humidity), and the major effects of temperature on the visual, compositional, and eating quality of each individual fruit or vegetable crop; finally, each chapter shows, by means of photographs, how the appearance of each selected fruit or vegetable is affected by storage time and temperature. Each fruit and vegetable was grouped according to its characteristics, so that chapter 1, "Subtropical and Tropical Fruits," includes grapefruit, orange, mandarin, mango, papaya, passion fruit, and carambola; chapter 2, "Pome and Stone Fruits," includes apple and peach; chapter 3, "Soft Fruits and Berries," includes blackberry, blueberry, currant, raspberry, and strawberry; chapter 4, "Cucurbitacea," includes cantaloupe, watermelon, and yellow squash; chapter 5, "Solanaceous and Other Fruit Vegetables," includes tomato, cape gooseberry, green bell pepper, eggplant, and sweetcorn; chapter 6, "Legumes and Brassicas," includes faba beans, snap beans, cabbage, cauliflower, broccoli, and Brussels sprouts; chapter 7, "Stem, Leaf, and Other Vegetables," includes asparagus, lettuce, witloof chicory, and mushrooms; and, finally, chapter 8, "Alliums," includes leek, green onion, and fresh garlic. For each selected fruit and vegetable, descriptions of the cultivar used, the place and season of harvest, the storage temperature, and the humidity conditions are included, as well as a description of each picture focusing on the important and visible changes in the appearance of the fruit or vegetable throughout storage at the different temperatures.

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CHAPTER 1

SUBTROPICAL AND TROPICAL FRUITS

Grapefruit
Orange
Mandarin
Mango
Papaya
Passion Fruit
Carambola
Bibliography

Color Atlas of Postharvest Quality of Fruits and Vegetables Maria Cecilia do Nascimento Nunes
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GRAPEFRUIT

Scientific Name: *Citrus paradisi* Macf.
Family: Rutaceae

Quality Characteristics

Good quality grapefruit has a turgid, smooth, glossy, and blemish-free peel. The fruit should be firm, and the flesh should have reached an adequate total soluble sugar (TSS)-to-acidity ratio and have low bitterness. Total soluble sugar content, acid content, TSS-to-acidity ratio, juice content, and color break are normally used worldwide as indicators of grapefruit maturity or quality, or both (Burns 2004a; Fellers 1991; Risse and Bongers 1994). The TSS-to-acidity ratio for grapefruit depends on the area of origin and even the time of year. For example, the minimum percentages of TSS, acid content, and TSS-to-acidity ratio acceptable in Florida grapefruit are 8.0, 7.0, and 7.5, respectively, whereas in Texas the percentages are 9.0 for TSS content and 7.2 for TSS–to-acidity ratio (Citrus Administrative Committee 2005; Grieson 2006). 'Marsh' white grapefruit grown in Florida (1992–1993 marketing season) contained approximately 52% juice, 10% total soluble solids, 1.3% acidity, and a total soluble solids content-to-acidity ratio of 7.6. (Risse and Bongers 1994). In general, the fruit of the white grapefruit contains about 91% water and 8% carbohydrates, with total sugars comprising 7.3%, lipids 0.1%, proteins 0.6%, and fiber 1% (USDA 2006). Pink and red grapefruits contain on average 88% water, 10.7% carbohydrates, 0.1% lipids, 0.8% proteins, and 1.6% fiber. Total sugar content averages 11 g per 100 g fresh weight, with major sugars being sucrose (3.5 g per 100 g fresh weight), glucose (1.6 g per 100 g fresh weight), and fructose (1.8 g per 100 g fresh weight) (USDA 2006). Depending on the cultivar, stage of maturity, and environmental factors during development in the field, as well as handling conditions during postharvest, the fruit of white, pink, and red grapefruits may contain between 26 and 61 mg of vitamin C per 100 g of fresh fruit (Nagy 1980; USDA 2006). White grapefruit also contains a high concentration of antioxidant compounds with high antioxidant capacity, such as phenolic compounds (Gorinstein et al. 2004). Red and pink grapefruits also contain generous amounts of lycopene (1,419 µg per 100 g fresh weight), β-carotene (686 µg per 100 g fresh weight), vitamin A (1,150 IU per 100 g fresh weight) (USDA 2006; Xu et al. 2006), and flavonones, mainly naringin, which give the tangy or bitter taste to the fruit (Peterson et al. 2006).

Optimum Postharvest Handling Conditions

Grapefruit is normally stored at about 10–15°C depending on the cultivar, growing area, season of harvest, and fruit maturity. A postharvest physiological disorder called postharvest pitting (PP) may develop in grapefruit held at warm temperatures (i.e., >10°C) and coated with a wax that strongly inhibits gas diffusion into the fruit. Storage of waxed fruit at these temperatures promotes high respiration, resulting in high internal carbon dioxide and ethanol concentrations and low internal oxygen levels, leading to anaerobic respiration. Compared to nonpitted fruit, pitted grapefruit also shows higher volatile content, namely limonene, which is released from the oil glands as a consequence of the anaerobic conditions (Dou 2003). To avoid PP, fruit are generally pre-cooled after harvest to a temperature below 10°C and maintained at 5–8°C during handling and distribution (Burns 2004a). Nonwaxed fruit or fruit with coatings that allow better gas diffusion should be stored at temperatures of 10°C or higher to prevent the development of chilling injury (CI).

Prompt pre-cooling after harvest helps to prevent PP and other peel disorders, such as stem-end rind breakdown and blossom-end clearing, helps to prevent the development of decay during storage, and slows respiration and water loss. A cooling delay of 12–24 hours or longer significantly increased PP in 'Marsh' grapefruit (Dou and Ismail 2000), whereas prompt pre-cooling of the fruit reduced blossom-end clearing, a disorder that appears as an external, wet, and translucent area at the blossom end of the fruit and often develops when grapefruit is exposed to high temperatures later in the season. Blossom-end clearing was reported to be lower in grapefruit that were pre-cooled to 16°C after being held at 37°C (Echeverria et al. 1999).

Pre-cooling to temperatures below 10°C can be harmful, especially to early season grapefruit, because it may cause CI and subsequent severe peel damage (Burns 2004a). More severe symptoms of CI were seen when grapefruit were stored at temperatures of about 3–4°C, when compared to grapefruit stored at higher or lower temperatures (Purvis 1985; Ritenour et al. 2003b). Although preconditioning the fruit for 7 days at approximately 16°C may reduce the development of CI, it may hasten the development of PP in grapefruit that are waxed prior to preconditioning (Ritenour et al. 2003b). Therefore, storage of waxed 'Marsh' white grapefruit and 'Star Ruby' at 7 or 8°C, respectively, seems to be the best compromise to minimize both PP and CI (Dou and Ismail 2000; Schirra 1992). Grapefruit storage at 90–95% relative humidity (RH) is preferable, especially during degreening in plastic bins, but RH should be lowered when fruit is in fiberboard cartons because water absorption by the cartons at higher RH weakens them. Optimum humidity levels avoid excessive loss of moisture and shriveled or dry appearance and reduce CI symptoms (Burns 2004a; Ritenour et al. 2003b).

Early citrus varieties grown in subtropical or tropical regions usually meet legal maturity standards before the peel attains the characteristic varietal color. This is because citrus fruit peel color is related more to climatic conditions—especially the presence of lower night temperatures—than to internal maturity. To obtain the desired peel color, mature but green grapefruit are normally exposed to ethylene (1–5 µL/L) prior to washing and waxing for 12–72 hours at temperatures between 21 and 29°C, depending on the cultivar and area of origin. The process is called degreening and is used to break down the chlorophyll to reveal the yellow-orange carotenoid pigments present in the flavedo (Burns 2004a; Ritenour et al. 2003a; Wardowski et al. 2006).

Temperature Effects on Quality

Environmental conditions after harvest significantly affect the quality and postharvest life of grapefruit. Temperatures that are too high or too low may result in severe damage and fruit loss. As mentioned previously, grapefruit exposed to temperatures lower than 7–10°C may develop CI symptoms characterized by peel pitting in which scattered areas of the peel collapse and darken. Pitting caused by exposure of the fruit to chilling temperatures is not restricted to the oil glands and may develop in any area of peel. CI may also develop as circular or arched areas of discoloration and scalding after about 6 weeks when grapefruit is stored at temperatures lower than 5°C (Burns 2004a; Ritenour et al. 2003b). However, resistance to chilling temperatures in grapefruit seems to be dependent on the type of cultivar and also on the time of harvest (Grierson 1974). For example, severe CI symptoms developed in 'Marsh' grapefruit stored for 78 days at 4°C or lower temperatures (Dou 2004), but no significant symptoms developed in 'Marsh' grapefruit from late season stored at 0°C for 3 weeks plus 1 week at 5°C or 10°C, followed by 3 weeks at 21°C (Kawada and Albrigo 1979). 'Star Ruby' grapefruit developed extensive pitting of the peel and fungal decay after 3 months of storage at 4°C plus 1 week at temperatures to 20°C (Schirra 1992). However, after 3–4 weeks of storage, grapefruit stored at 5 or 7.5°C showed more severe CI symptoms than did fruit stored at 2.5°C (Purvis 1985). Conversely, 'Star Ruby' grapefruit did not show clear evidence of CI, even after storage for more than 16 weeks at 6°C (Pailly et al. 2004), but in another study, 'Star Ruby' grapefruit stored at 8°C developed slight CI symptoms and at 12°C symptoms were negligible (Schirra 1992). In 'Thompson' pink grapefruit, pitting was four times greater in fruit stored at 1°C than in fruit stored at 10°C (Miller et al. 1990). Although no CI was observed in 'Marsh' grapefruit stored for 109 days at 5°C (Purvis 1983), 6% of 'Marsh' grapefruit developed pitting when stored for 3 weeks at 10°C, and pitting increased to about 21% after 4 weeks of storage (Miller et al. 1991).

In addition to cultivar variations, harvest season, and geographic location, differences in susceptibility to CI within the same cultivar may be also attributed to postharvest treatments applied to the fruit. For example, preconditioning of grapefruit at higher temperatures before transfer to a lower temperature may delay development of CI. Conditioning grapefruit at 21°C for 8 days prior to storage at 5°C delayed the development and intensity of CI compared to fruit stored continuously at 5°C (Purvis 1985). Likewise, storage of grapefruit at 10, 16, or 21°C for 7 days significantly reduced the development of CI during subsequent storage for 21 days at 1°C. CI was minimal in fruit stored continuously at 16°C for 28 days or conditioned at 16°C and then placed at 1°C. Conversely, 17.2% of the grapefruit stored continuously at 1°C for 28 days showed CI symptoms after storage (Hatton and Cubbedge 1982).

An intermittent warming regimen of 21 days at 2°C, followed by 7 days at 13°C for 12 weeks, also helped to reduce CI symptoms in grapefruit compared to fruit stored continuously at 2°C (Cohen et al. 1994). In addition, hot-water dipping for 2 minutes at 50°C helped to reduce CI by 61% in 'Marsh' grapefruit during storage at 1°C (Wild 1993). When 'Star Ruby' grapefruit was dipped in hot water at 53°C for 2 minutes, followed by 6 weeks of storage at 2°C plus an additional week at 20°C, CI and decay were significantly reduced, without impaired fruit quality (Porat et al. 2000b).

Wax coating may also help to prevent the development of CI in grapefruit stored at temperatures lower than those recommended. For example, waxed grapefruit stored for 120 days at 0.6, 2, 4, and 7°C and approximately 92% humidity showed a CI rate of 11, 37, 39, and 3%, respectively, whereas nonwaxed fruit had a CI rate of 96, 13, 21, and 1%, respectively (Dou 2004).

The previously mentioned PP resembles symptoms of CI, except that CI tends to affect the peel between oil glands, whereas PP consists of clusters of collapsed oil glands. Discoloration of the peel caused by CI is of a darker brown color than PP. Symptoms of PP begin as slight depressions on the peel in regions directly above the oil glands that turn a bronze color after a few days (Petracek et al. 1995). PP symptoms develop within the first week after storage, whereas CI symptoms often develop after 3 or more weeks at chilling temperatures. PP at nonchilling temperatures may also be caused by sudden changes from low (e.g., 30%) to high (e.g., 90%) relative humidity, even in nonwaxed fruit (Alférez and Burns 2004; Alférez et al. 2005).

Toughening and drying of grapefruit segments, known as granulation, or section-drying, is a physiological disorder that affects the juice vesicles. They become larger, with less juice, tougher, discolored, and with lower soluble sugars, acidity, and ascorbic acid contents (Burns and Albrigo 1998; Sharma et al. 2006). Granulation seems to result from the interaction of fruit maturity, size, and storage conditions. This disorder, which can start in grapefruit while on the tree, may also develop or increase during storage under inadequate conditions. For example, grapefruit stored for 60 days at 21°C developed higher levels of granulation than fruit left on the tree, and larger and late-harvested grapefruit were more affected than small and early season fruit (Burns and Albrigo 1998; Sharma et al. 2006; Shu et al. 1987).

Hot-water treatments, normally used to reduce fruit fly infestation, may also affect the quality of grapefruit. For example, immersion of 'Marsh' grapefruit in hot water at 48°C for 2 hours resulted in increased weight loss and softening and discoloration of the peel and promoted peel pitting, scalding, and decay after 4 weeks of storage at 13°C (McGuire 1991). However, fruit vapor-heated for 5 hours at 43.5°C, followed by storage for 4 weeks at 10°C plus 1 week at 21°C, showed reduced pitting caused by exposure to low temperature (CI), without increased weight loss, changes in peel color, soluble solids content, acidity, or pH, but the fruit were slightly softer when compared to non–vapor-heated fruit (Miller and McDonald 1991; Miller et al. 1991). Vapor heat treatment at 43.5°C for about 240 minutes reduced the incidence of rind aging by 45% in 'Marsh' and 'Ruby Red' grapefruit, after 5 weeks of storage at 16°C (Miller and McDonald 1992). In general, the higher the temperature of the air during the heat treatment, the more severe the heat damage to the fruit. Weight loss, discoloration, loss of firmness, susceptibility to scalding, and decay also increased as the temperature of the heat treatment increased. Hot-air treated 'Marsh' grapefruit harvested at mid-season tolerated well an exposure for 3 hours at 48°C or 2 hours at 49°C, followed by storage at 13°C (McGuire and Reeder 1992). Finally, 'Ruby Red' grapefruit exposed to a constant temperature forced-air treatment at 46°C for 300 minutes showed no external injury, lower acidity, and better flavor than non–heat-treated fruit, whereas soluble solids and soluble solids-to-acidity ratio did not differ from those of the non–heat-treated fruit (Shellie and Mangan 1996).

Decay is a frequent problem in grapefruit grown in humid regions, such as Florida (Burns 2004a). 'Marsh' and 'Ruby Red' grapefruit stored continuously at 10 or 16°C showed, on average, 0.7 and 1.8% decay, respectively, after storage for 28 days. In fruit stored at 1°C, decay was approximately 0.2% after 28 days of storage. However, after transfer for 7 or 14 days at 21°C, decay significantly increased to 3.8 or 8.3%, respectively (Hatton and Cubbedge 1982). Similarly, after 2 months at 4°C, decay in 'Marsh' grapefruit was 24% and increased to 67% after 4 months (Dou 2004). Although decay development was slower in 'Star Ruby' grapefruit stored at 4°C when compared to fruit stored at 8 or 12°C, decay significantly increased upon transfer to 20°C (Schirra 1992). Conditioning 'Marsh' grapefruit for 3 days at 34.5°C at high humidity (90–100%) before storage at 10°C reduced the development of *Penicillium* rot compared to fruit stored immediately at 10°C (Chun et al. 1988). In a study involving household storage, refrigerated grapefruit (standard home refrigerator) had a better appearance, firmness, and taste and had less decay and stem-end rind breakdown than fruit held at ambient temperature (kitchen countertop) (Ismail and Wilhite 1991), most likely due to excessive loss of moisture during exposure at ambient higher temperatures compared to refrigerated storage.

'Ruby Red' grapefruit held at room temperature appeared shriveled due to excessive weight loss, and desiccation also resulted in a significant decrease in peel thickness and firmness (Ismail and Wilhite 1991). Loss of firmness and permanent deformation was correlated with increased weight loss during storage of grapefruit (Kawada and Albrigo 1979) and was influenced by cell-wall polysaccharide content (Muramatsu et al. 1996). Holding 'Marsh' grapefruit for 10 days at ambient temperature, followed by 4 weeks at about 10°C, and then 3 more weeks at ambient temperature, resulted in increased weight loss and fruit softness (Gilfillan and Stevenson 1976). Weight loss in 'Marsh' grapefruit also increased with increasing storage time. However, weight loss was higher in grapefruit stored at 13°C than at 2°C, but after transfer to 20°C the fruit that was exposed to the lower temperature lost more additional weight than that stored at the higher temperature. The lower weight loss observed in fruit stored at 2°C compared to 13°C was attributed to the lower transpiration rate at lower temperature (Cohen et al. 1994). Humidity levels of the surrounding environment also have a great effect on the weight loss of grapefruit during storage. For example, weight loss per day in grapefruit stored at 20°C and 90% humidity was 0.3% and about 0.4–0.5% when stored at the same temperature but lower humidity (30%). After 20 days at 20°C, weight loss of grapefruit stored at lower humidity was about two times greater than that of fruit stored at higher humidity. In addition, the season of harvest seems to influence the rate of water loss during the postharvest period (Gilfillan and Stevenson 1976; Shu et al. 1987). For example, weight loss of 'Marsh' grapefruit stored for 8 weeks at 21°C increased with harvest date from February to May, and attained the highest levels (2.8%) in fruit harvested in May (Shu et al. 1987), probably due to changes in the structure and thickness of the fruit's naturally waxed cuticle and albedo throughout the season. In addition, weight loss was higher in washed compared to nonwashed grapefruit. Thus, after 20 days at 20°C, weight loss in washed fruit stored at 90 and 30% humidity was about 6 and 12%, respectively, whereas in unwashed fruit stored under the same conditions weight loss was 4 and 8%, respectively (Alférez and Burns 2004). Commercial washing of grapefruit contributes to the removal of the natural wax coating, which results in greater susceptibility to water loss compared with nonwashed fruit. For that reason, the natural wax is usually replaced by wax coatings such as shellac, carnauba, or polyethylene (Hall and Sorenson 2006). However, fruit coatings may restrict gas exchange through the peel and result in PP and the accumulation of off-flavors and volatiles (e.g., from ethanol and acetaldehyde accumulation in the juice) that impair the taste (Shi et al. 2005). Although rarely used commercially, individual film wrapping of grapefruit can effectively reduce weight loss (Goldman 1989; Kawada and Albrigo 1979; Purvis 1983; Shu et al. 1987). For example, compared to waxed fruit, polyvinylchloride, polyolefin, and perforated polyolefin or polybutadiene significantly reduced weight loss in 'Marsh' grapefruit stored at 15.5, 21, or 29.5°C after 8 weeks of storage (Shu et al. 1987).

Composition and nutritional value of grapefruit are also affected by postharvest environmental conditions. 'Star Ruby' grapefruit stored for more than 16 weeks at 6°C had higher acidity, lower juice content, and lower total soluble solids-to-acidity ratio than fruit stored at 10°C (Pailly et al. 2004). Likewise, exposing 'Marsh' grapefruit to simulated shipping and handling conditions, that is, between the time the fruit was packed and sold (10 days at ambient temperature, followed by 4 weeks at about 10°C, and then 3 more weeks at ambient temperature) resulted in increased soluble solids content, but no changes in acidity were observed, compared to initial values (Gilfillan and Stevenson 1976). Increases in the soluble solids content of some citrus fruit during storage might not always be related to changes in the total or individual sugar content of the fruit, as sometimes changes in sugars do not account for the increase in soluble solids content (Echeverria and Ismail 1990). However, in another study, the acidity and soluble solids content of grapefruit juice stored for 1, 3, or 4 months at 4, 8, or 12°C decreased with increasing storage time and temperature (Schirra 1992), most likely due to increased respiration rate at higher temperatures, which often leads to accelerated consumption of sugars and organic acids, particularly during extended storage. Season of harvest also has a significant effect on the taste and juice quality of stored grapefruit. At the end of California and Arizona grapefruit seasons, reduced juice acceptability was associated with low acid content, decreased soluble solids content, lower TSS-to-acidity ratio, and development of off-flavors. Low TSS-to-acidity ratio results in a grapefruit with a tart and sour flavor (Fellers 1991).

In general, ascorbic acid content of grapefruit decreases with increasing storage temperature. For example, a low-temperature regimen did not contribute to ascorbic acid degradation, whereas holding the fruit for 7 days at 15°C before cold storage significantly reduced the ascorbic acid levels (Biolatto et al. 2005). Although waxed fruit had higher juice, soluble sugar, and acid content, nonwaxed grapefruit had a slightly higher content of ascorbic acid than nonwaxed fruit after storage for 81 days at 21°C (Purvis 1983).

Flavor and aroma volatile content of grapefruit also increased with increased storage temperature. Nootkatone is a flavor compound that contributes to the characteristic flavor and aroma of grapefruit; it increases with increasing storage time and temperature. In 'Marsh' grapefruit the levels of nootkatone increased with storage, but the increase was higher when fruit was stored at 21°C than at 4.5°C (Biolatto et al. 2002). Wax application and cold storage (4°C) were also reported to reduce the levels of nootkatone in 'Marsh' grapefruit 14 or 28 days after wax application (Sun and Petracek 1999).

Time and Temperature Effects on the Visual Quality of 'Marsh' Grapefruit

'Marsh' grapefruits shown in Figures 1.1–1.8 were harvested at the legal maturity standard for Florida from a commercial operation in Fort Pierce, Florida, during the spring season (i.e., March). Promptly after harvest (within 6 hours), fresh grapefruit was degreened according to the recommended procedures for degreening Florida citrus (Ritenour et al. 2003a; Wardowski et al. 2006). Subsequently, fruits were washed with water, but not waxed, and stored at five different temperatures (0.5 ± 0.3°C, 5.0 ± 0.2°C, 9.4 ± 0.4°C, 14.40 ± 0.4°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Visual quality of 'Marsh' grapefruit changes during storage, and the changes are greatly dependent on the storage temperature. Major visual changes in grapefruit stored at temperatures lower than 10°C are attributed to CI and aggravate when the fruit is transferred to ambient temperatures. In fruit stored at temperatures greater than 5°C, major changes in the visual quality result from changes in fruit coloration, softening, and development of decay.

Some minor defects (i.e., small brownish spots) develop in the peel of 'Marsh' grapefruit during continuous storage at 0°C after 14 days but do not increase much further during the remaining storage period (Figure 1.1). However, in grapefruit held at 0°C for 70 days, pitting of the skin develops very quickly after transfer to 20°C and is severe within only 2 additional days (Figure 1.2). Pitting of the skin aggravates with exposure time to 0°C, and after 76 days severe pitting develops and the surface of the fruit appears completely covered with rusty sunken areas.

Grapefruit stored continuously at 5°C maintains acceptable visual quality for up to 49 days of storage (Figure 1.3). However, after that time, slight aging of the rind develops at the stem-end of the fruit and aggravates during further storage. Upon transfer of the fruit stored for 70 days at 5°C for 2 additional days at 20°C, pitting of the skin develops and stem-end breakdown aggravates (Figure 1.4).

'Marsh' grapefruit stored at 10°C maintains acceptable visual quality during 76 days of storage, and no CI symptoms or postharvest peel pitting are observed in fruit stored at this temperature (Figure 1.5). The color of the fruit changes during storage from a greenish-yellow at the time of harvest to a yellowish-orange after 21 days of storage.

After 35 days at 15°C 'Marsh' grapefruit develops decay at the stem-end, which aggravates with increased storage time (Figure 1.6). After 54 days at 15°C, decay spreads from the peel to other parts of the fruit, affecting not only the albedo and flesh at the stem-end but also the peel and albedo at the blossom-end (Figure 1.7).

Although not visually perceived, 'Marsh' grapefruit stored at 20°C shows increased softening during storage, and after 49 days softening is objectionable (Figure 1.8). Firmness of the fruit decreases with continued storage and after 70 days the fruit is extremely soft and cedes very easily to finger pressure. The color of the peel changes during storage from a greenish-yellow at the time of harvest to a light yellowish color.

Overall, ‘Marsh’ grapefruit changes in fruit coloration, softening, and symptoms of CI caused by exposure to cold temperatures, such as pitting and decay, are the most important visual factors that limit the postharvest life of the fruit. ‘Marsh’ grapefruit stored at 10 and 15°C maintains a good quality for longer periods (76 and 54 days, respectively) than grapefruit stored at lower or higher temperatures. Grapefruit stored at 0, 5, and 20°C retains an acceptable visual quality for 21, 49, and 35 days, respectively, but quality deteriorates very quickly afterward.

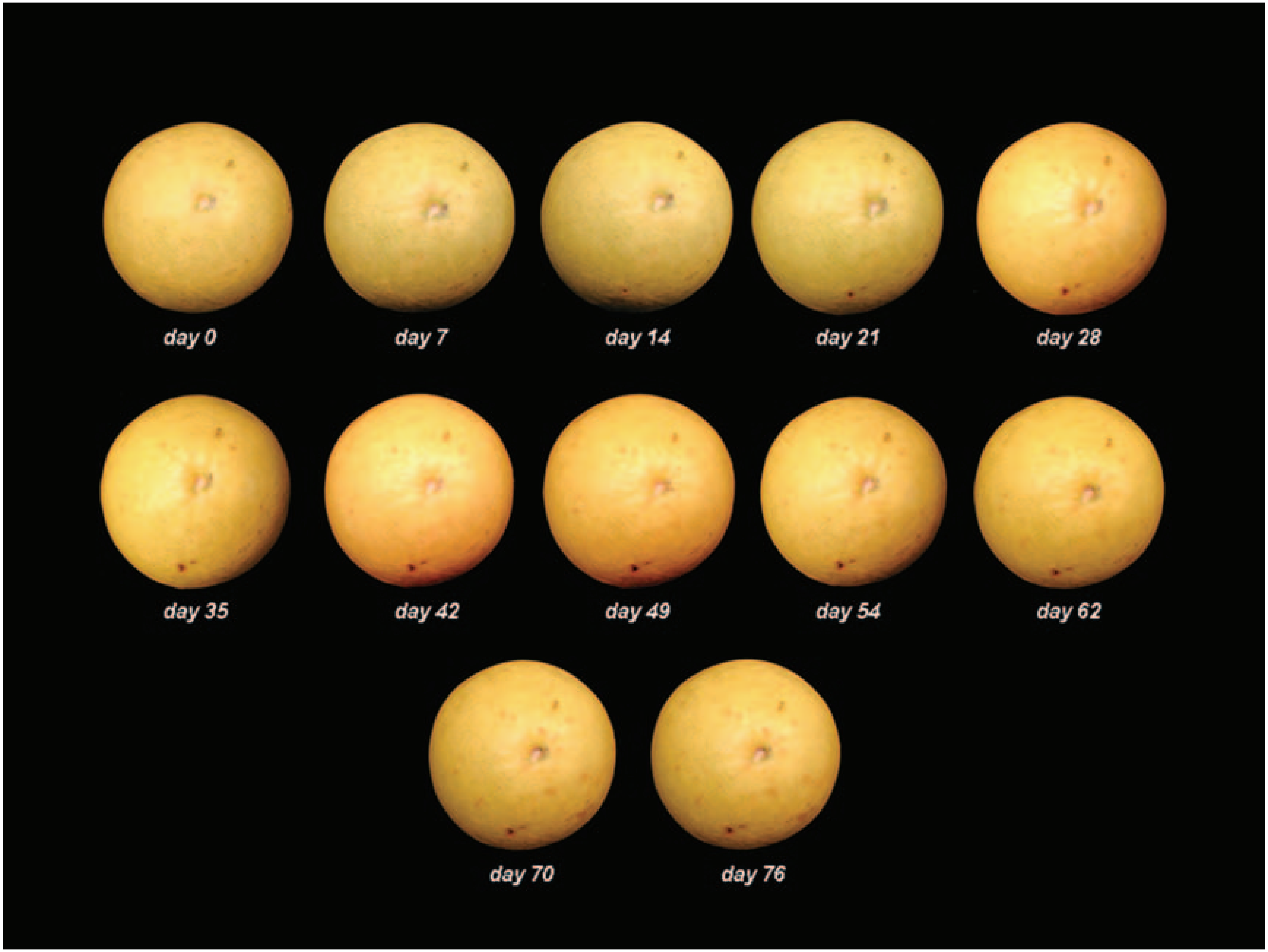
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Figure 1.1. Appearance of ‘Marsh’ grapefruit stored for 76 days at 0°C. After 21 days small dark spots are evident in the peel of the fruit.

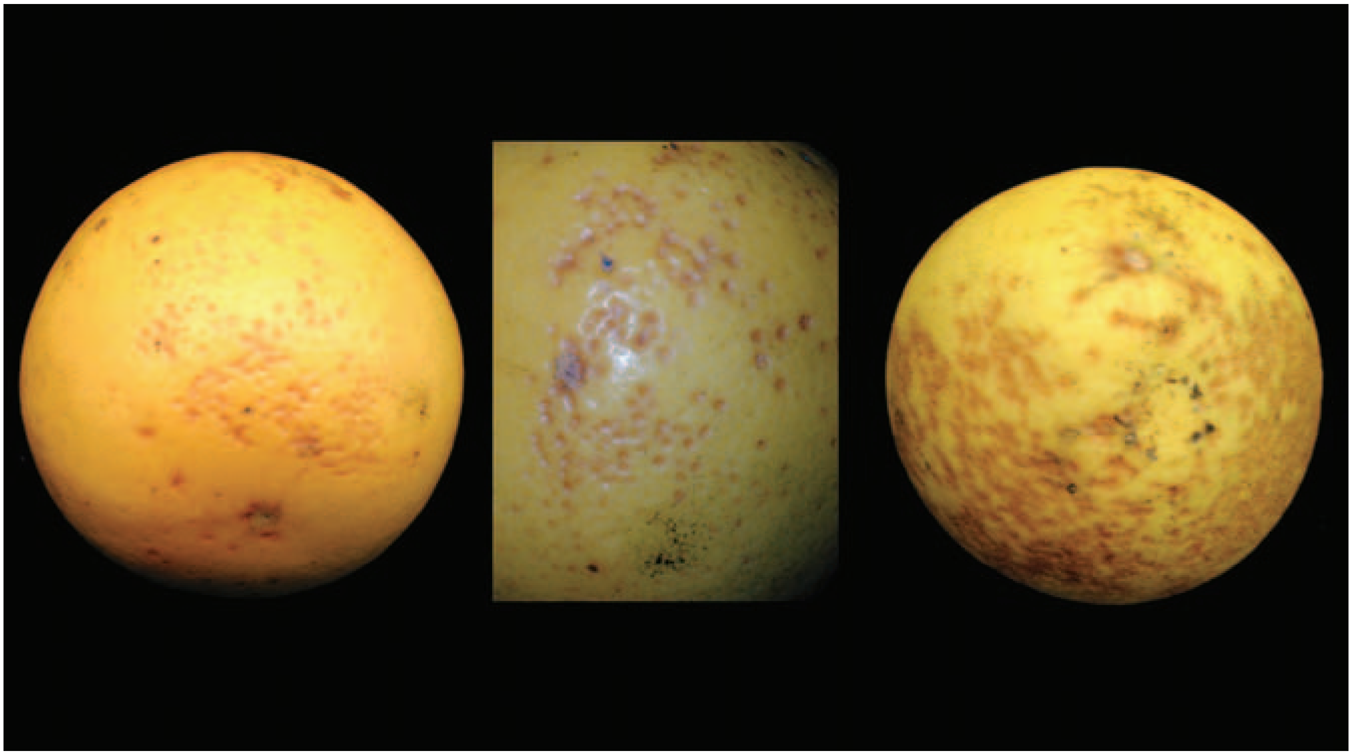

Figure 1.2. Chilling injury (pitting of the peel) in 'Marsh' grapefruit after storage for 70 (left and center) and 76 days (right) at 0°C plus 2 days at 20°C. Pitting develops very quickly after transfer to nonchilling temperature, and aggravates with the exposure period to 0°C.

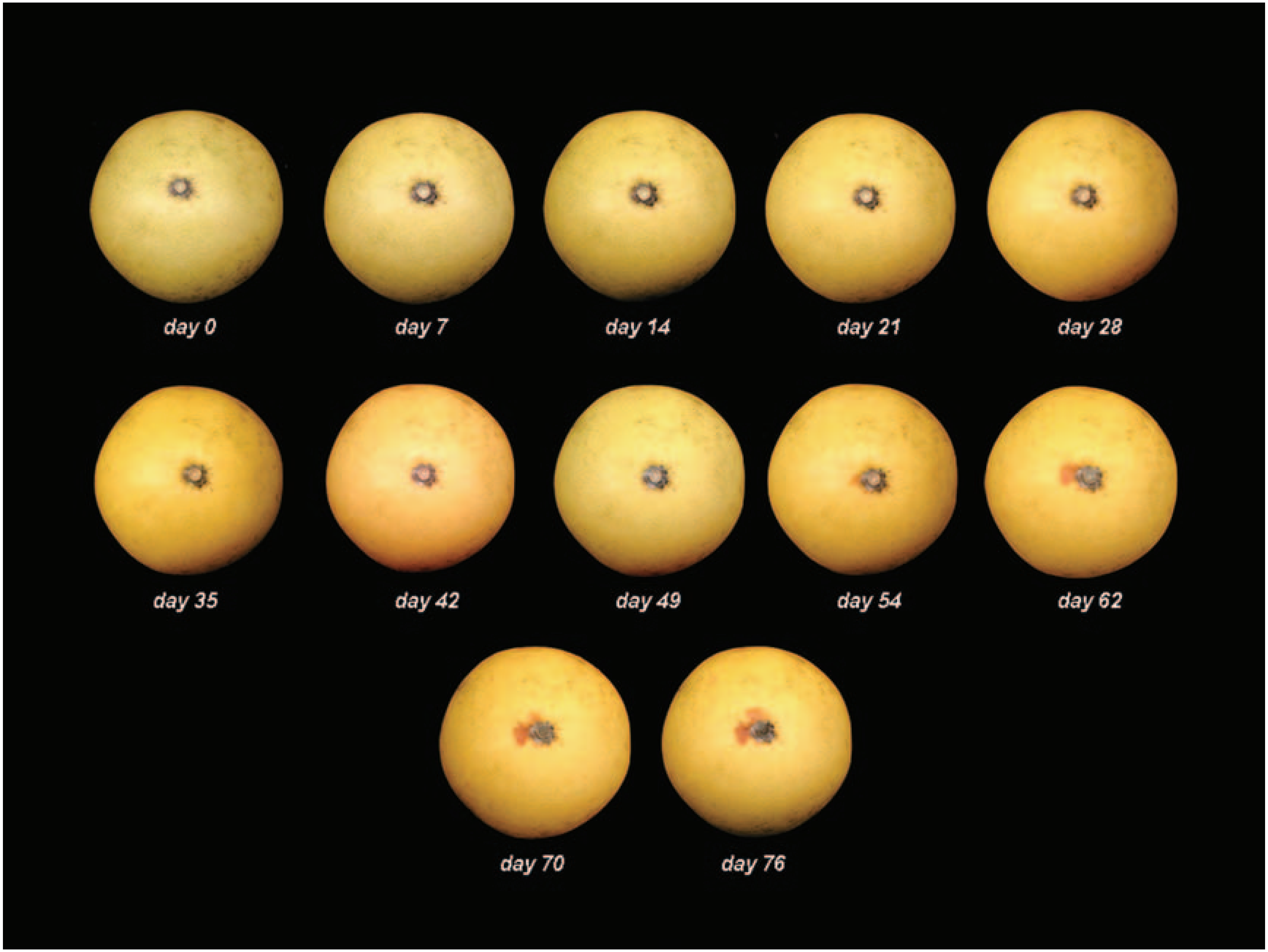
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Figure 1.3. Appearance of ‘Marsh’ grapefruit stored for 76 days at 5°C. Fruit maintains an acceptable visual quality up to 49 days of storage, after which some stem-end breakdown develops.

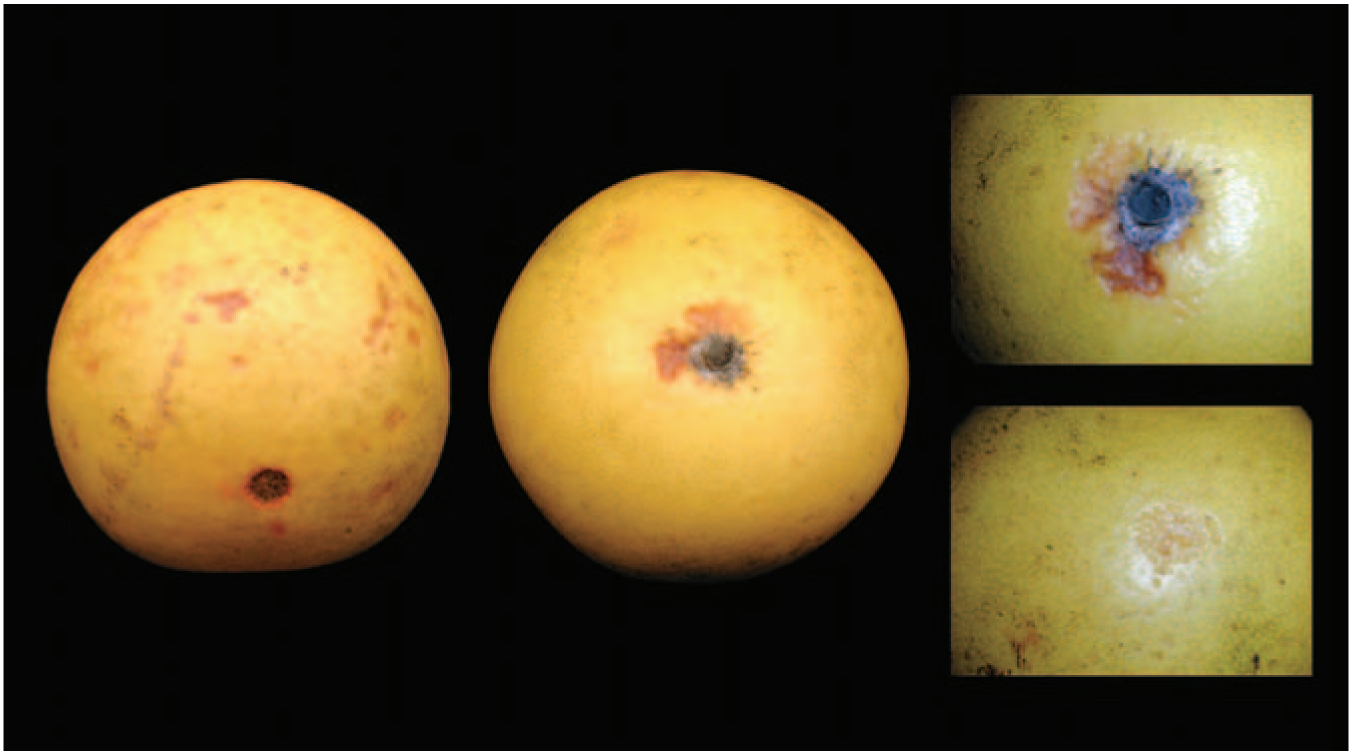

Figure 1.4. Chilling injury (pitting of the skin) in 'Marsh' grapefruit after storage for 70 (left) and 76 days (center and right) at 5°C plus 2 days at 20°C.

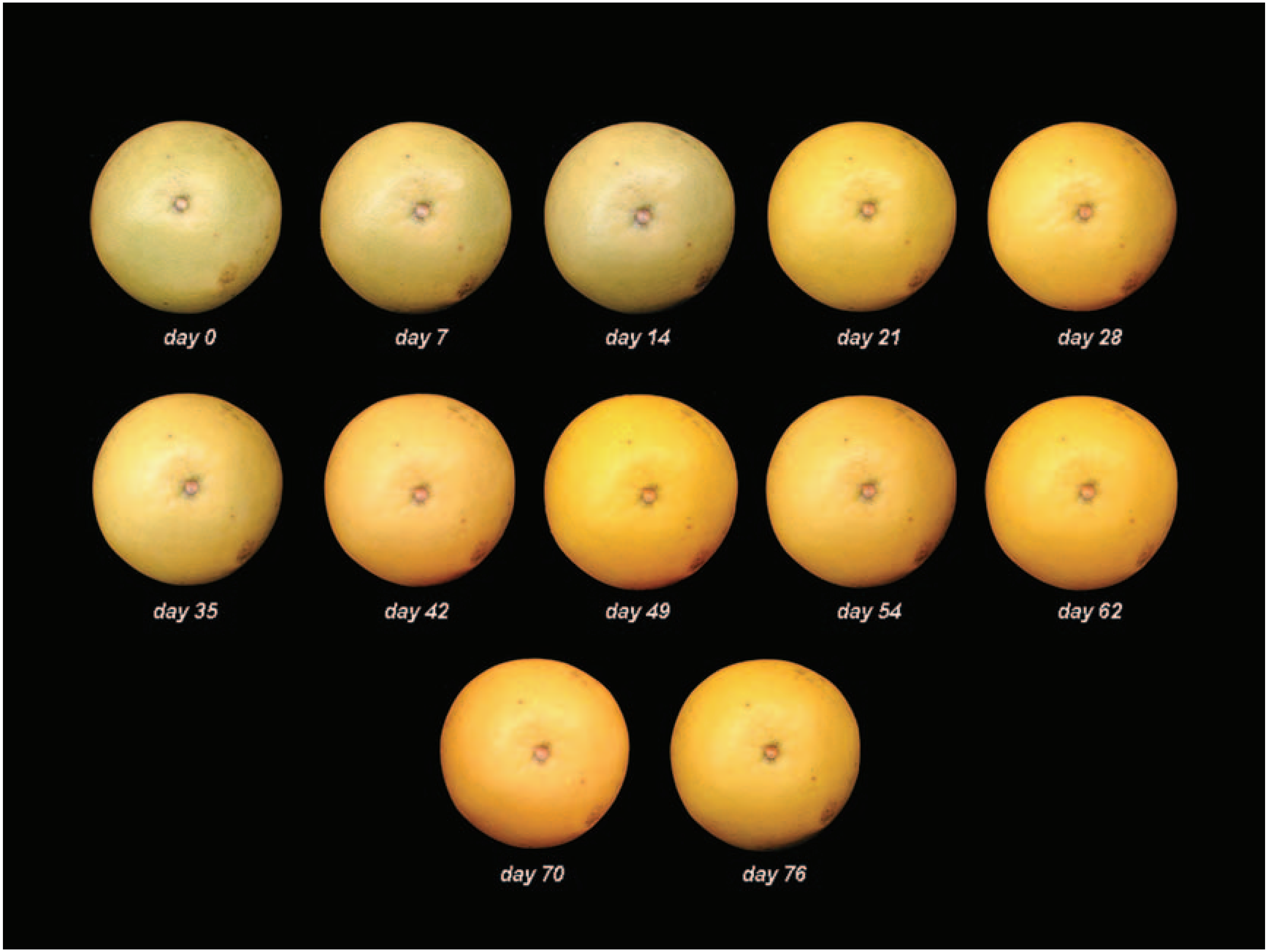
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Figure 1.5. Appearance of 'Marsh' grapefruit stored for 76 days at 10°C. After 21 days of storage the fruit develops a deeper yellowish color and maintains an acceptable visual quality up to 76 days of storage.

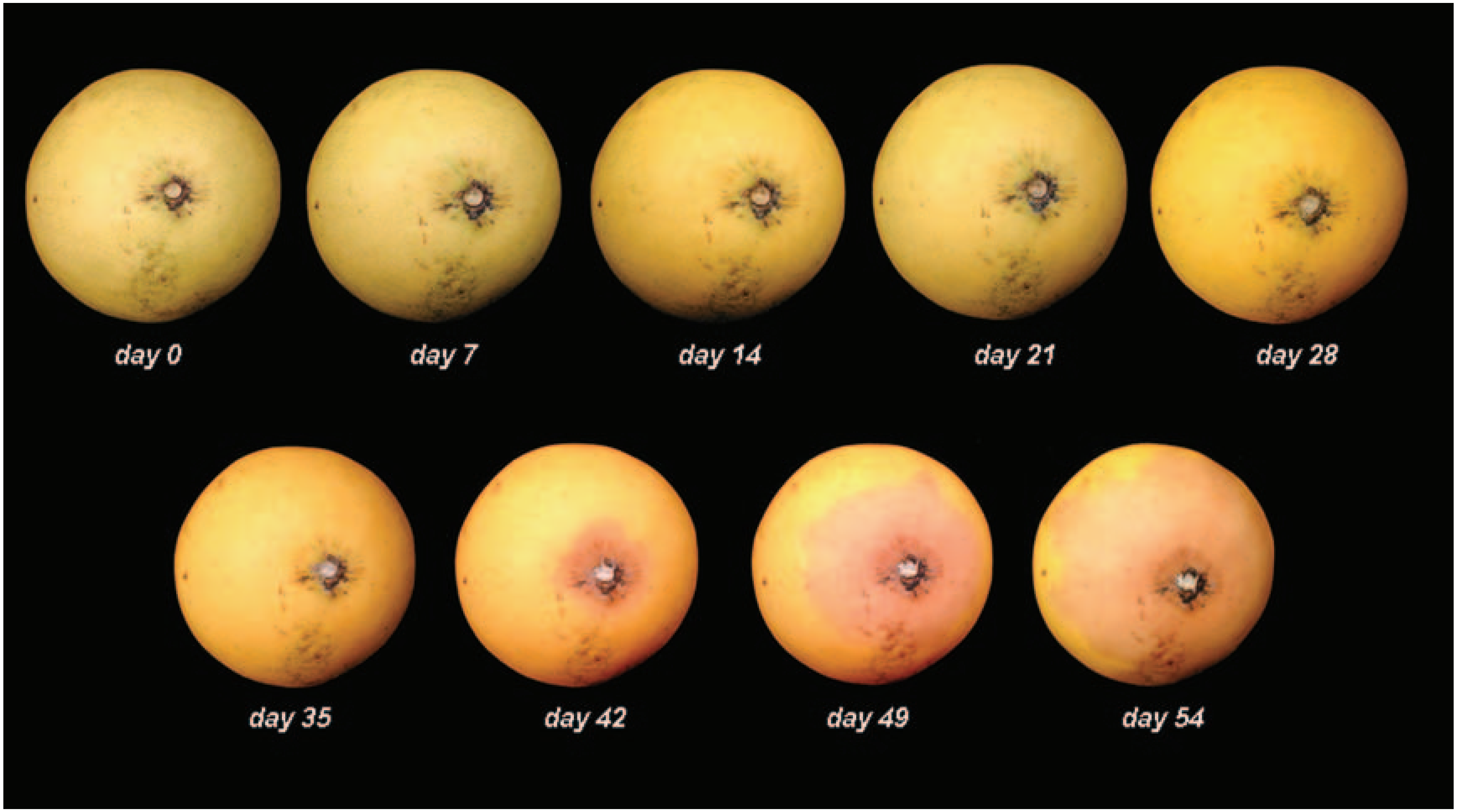
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Figure 1.6. Appearance of 'Marsh' grapefruit stored for 54 days at 15°C. Stem-end rot develops after 35 days and attains severe levels after 54 days.

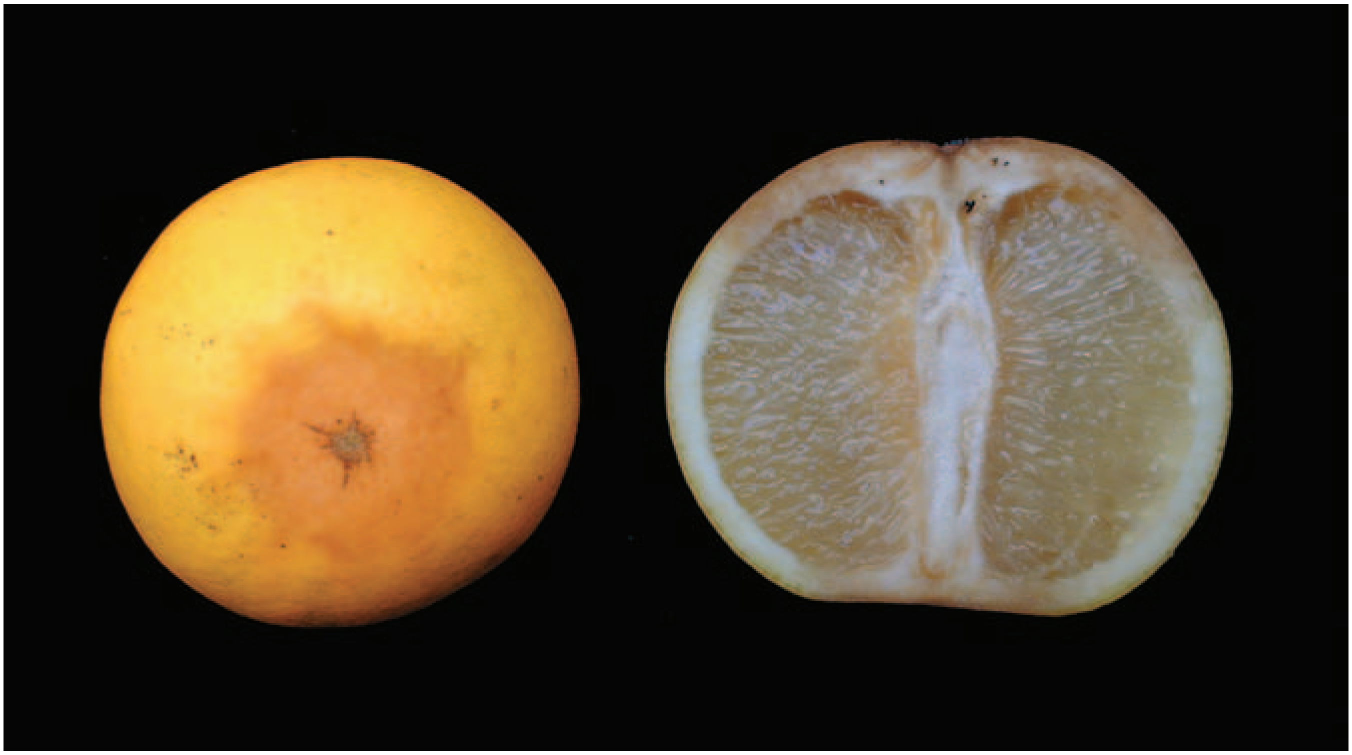
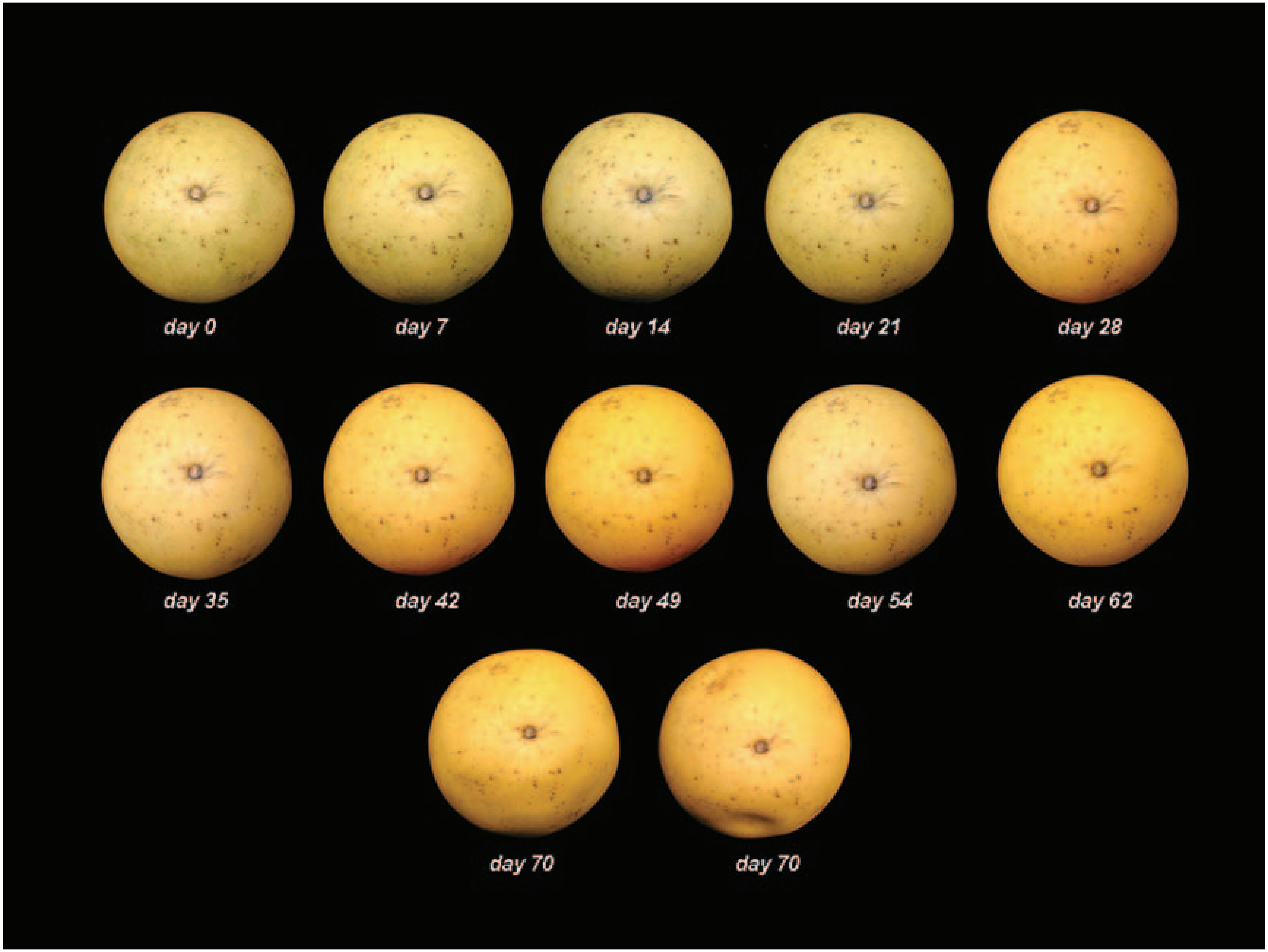


Figure 1.7. Blossom-end and internal appearance of 'Marsh' grapefruit stored for 54 days at 15°C. Decay spreads from the peel stem to the blossom-end and affects the fruit albedo and flesh.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day 70
day 70

Figure 1.8. Appearance of 'Marsh' grapefruit stored for 70 days at 20°C. Fruit shows increased softening during storage, and after 70 days the fruit is extremely soft and cedes very easily to finger pressure.

ORANGE

Scientific Name: *Citrus sinensis* L. Osbeck
Family: Rutaceae

Quality Characteristics

There are many orange varieties grown worldwide, but probably the most common cultivars are the round oranges such as 'Valencia,' 'Hamlin,' 'Pineapple,' and 'Shamouti'; navel oranges like 'Washington navel'; blood or pigmented oranges like 'Moro' or 'Tarocco'; and low-acid oranges like 'Succari.' Depending on the cultivar, the shape of the orange can be round to oblong, and the fruit may be seeded or seedless. The peel color in mature fruit grown in climates with sufficiently low night temperatures changes from green to light or deep orange. Under tropical or warm subtropical environments the peel may remain green until placed under degreening conditions (see discussion in the "Grapefruit" section). The condition of the peel is a very important attribute, as it influences not only the visual quality and consumer acceptance but also fruit internal quality (Camarena et al. 2007). Therefore, a good quality orange must be mature, and the peel should be firm, turgid, have a smooth texture, and its characteristic orange color should be distributed uniformly over the fruit surface.

Maturing fruit also experience a gradual increase in juice content, a decline in acidity and pectic substances, and an increase in soluble solids content (Clements 1964; Hutton and Landsberg 2000; Peleg et al. 1991; Sinclair and Jolliffe 1961a). Ascorbic acid content increases as the fruit matures, but then declines with increasing fruit weight and maturity (Eaks 1964). Other quality indicators used as maturity indices are based not only on the peel appearance and percentage of color break but also on the soluble solids content, acidity, soluble solids content-to-acidity ratio, and juice content. Depending on the growing area and season of harvest, specific maturity regulations are used. For example, Florida oranges should have a minimum acidity of 0.4%, 8.5–9.0% soluble solids content, 10.00–10.25 soluble solids content-to-acidity ratio, and a minimum juice content of approximately 17 L of juice per 22 kg of fruit. In California and Arizona fruit with yellow-orange color on less than 25% of its surface should have a soluble solids content-to-acidity ratio of 8 or higher, whereas in Texas fruit with minimum maturity must have an 8.5–8.9% soluble solids content, with a soluble solids content-to-acidity ratio of 10 or higher, and a minimum juice content of approximately 17 L per 22 kg of fruit (Ritenour 2004). According to regulations set forth by the Commission of the European Communities, depending on the variety, oranges should have a minimum juice content of 30–35% by weight of fruit, with coloring typical of the variety (Commission of the European Communities 2002). In Australia, maturity standards for oranges include 33% juice by weight, 1.92–2.24% as maximum acid content, 8% total soluble solids, and a 5.5–7.0 soluble solids content-to-acidity ratio (Grierson 2006; Hutton and Landsberg 2000). Physical and perceived attributes, such as juiciness, skin quality, sweetness, and texture, were ranked as the most important quality attributes when purchasing oranges. Juiciness, skin quality and sweetness, and texture were considered by 96, 90, and 80% of the respondents, respectively, to be somewhat important or very important (Poole and Baron 1996).

In general, orange fruit contains about 87% water, 17% carbohydrates, 0.7% proteins, and 2.4% fiber (USDA 2006). Depending on the cultivar, stage of maturity, environmental conditions during development in the field, and postharvest handling conditions, orange fruit may contain between 31 and 79 mg of vitamin C and 71 μg of β-carotene per 100 g of fresh fruit (Eaks 1964; Nagy 1980; USDA 2006).

Optimum Postharvest Handling Conditions

To reduce water loss and decay, and to extend postharvest life, oranges should be pre-cooled promptly after harvest. Because hydro-cooling may increase the risk of spreading decay organisms, the most used cooling methods are room-cooling and forced-air cooling (Ritenour 2004). After pre-cooling, the fruit should be held at its optimum stored temperature, which varies depending on the cultivar and region of harvest. Oranges from Florida and Texas should be stored between 0 and 1°C, whereas oranges from California and Arizona should be stored between 3 and 8°C (Ritenour 2004). Relative humidity should be kept around 90%. 'Shamouti' oranges from Israel should be stored at 5°C (Yehoshua et al. 2001), whereas blood oranges from Italy require temperatures higher than 8°C (Schirra et al. 2004). Storage temperatures vary depending on the cultivar susceptibility to CI. Oranges from Florida or Arizona seldom show signs of CI, whereas oranges from California, Texas, and other parts of the world require higher storage temperatures to prevent CI (Ritenour 2004).

Prior to washing and waxing, green oranges are normally exposed to ethylene (1–5 μL/L^{-1}) for periods of 12–72 hours at temperatures between 21 and 29°C, depending on the cultivar and area of origin. The process is called degreening and is used to break down chlorophyll and promote characteristic orange color development (Hearn 1990; Ritenour et al. 2003a; Wardowski et al. 2006).

Temperature Effects on Quality

Temperatures encountered during handling and distribution greatly affect the visual, eating, and compositional quality of fresh orange fruit. Very often oranges are transported from the packinghouse to the warehouse without refrigeration and displayed in stores at ambient temperature (Hagenmaier 2000). Loss of flavor and firmness, increased weight loss, and, as a result, peel and flesh desiccation often occur when fruit is handled under inadequate conditions.

Firmness of orange fruit is strongly related to storage time and temperature; as temperature increases, a fast decrease in fruit firmness is usually observed. In addition, the texture of orange flesh is determined by the condition of the juice vesicles and their cell walls (Ting 1970). Muramatsu et al. (1996) showed that the loss of firmness in the navel orange was influenced by cell-wall polysaccharide content. When oranges stored at 8°C were transferred to 20°C, a rapid softening was observed (Olmo et al. 2000). Likewise, during storage between 20 and 23°C 'Navelina' oranges became softer, the peel thickness decreased, and the level of dehydration increased due to loss of moisture. In 84 days at temperatures between 20 and 23°C, dehydration changed from 0.06 to 2.52 kg/m^2, whereas peel thickness decreased from 4.3 to 2.9 mm. The albedo became thinner and more compact, the density of the peel decreased, turgidity forces increased, and firmness decreased due to aging of the fruit (Camarena et al. 2007). Increased softness was also observed in oranges exposed to 33°C for 24–72 hours, followed by storage for 2 months at 4°C (Plaza et al. 2003).

Changes in fruit firmness may also occur due to granulation or section drying, which is a physiological disorder that affects the juice vesicles and results in toughening and drying of the orange segments. Compared to a healthy orange, fruit affected by granulation showed larger, tougher, and discolored juice vesicles, with less juice, higher pectic material content, higher pH, and lower soluble sugars, acidity, and ascorbic acid contents (Burns and Albrigo 1998; Sharma et al. 2006; Sinclair and Jolliffe 1961b;). 'Valencia' oranges held at ambient temperature often show severe symptoms of stem-end breakdown and decreased peel thickness due to desiccation (Ismail and Wilhite 1991). Because a decrease in firmness is strongly related to increased weight loss (Olmo et al. 2000), raising humidity levels during postharvest handling helps reduce orange fruit desiccation and excessive softening. High relative humidity during storage of 'Lanes Late' oranges not only reduced fruit moisture loss and maintained fruit firmness but also reduced CI symptoms (Henriod 2006; Henriod et al. 2005).

Chilling injury symptoms in oranges include peel pitting, brown staining, and increased decay incidence. Sunken and discolored lesions on the flavedo around the stem-end and rind brown-staining have also been associated with CI in oranges (Davis and Hofmann 1973; Henriod et al. 2005). Symptoms of CI usually increase with storage time and aggravate when fruit is removed from the chilling temperature. For example, 'Lanes Late' navel oranges stored at −1°C showed about 1.6- and 2.0-fold higher incidence and severity of CI, respectively, than fruit stored at 1 or 3°C, and the symptoms aggravated after transfer to 22°C (Henriod et al. 2005). After 4 and 12 weeks of storage, severity of CI in 'Valencia' oranges stored at 0°C increased from slight to moderate, respectively, and the symptoms aggravated with increased ethylene levels in the surrounding environment (Yuen et al. 1995). When 'Temple' oranges were stored at approximately 1°C for 10 weeks, development of pitting affected 10% of the fruit, whereas 14% of the oranges developed brown-staining after transfer to 21°C for 2 additional weeks. 'Valencia' oranges stored at 1°C for 12 weeks did not develop pitting but showed some signs of aging, such as depressed areas near the stem-end (Davis and Hoffmann 1973). However, 'Valencia' oranges stored for 6 months at 4°C plus 1 week at 20°C developed CI symptoms, which appeared in the form of discolored, small pitted areas and skin depressions irregularly distributed over the fruit surface. The symptoms aggravated with exposure time to chilling temperature, and after 6 months CI index was almost two times higher compared to a 2-month exposure (Erkan et al. 2005). After 5 weeks at 3°C, no CI symptoms were observed in 'Olinda' oranges, whereas after 8 weeks the symptoms were very minor. After 13 weeks, slight to moderate CI affected 5% of the fruit, whereas 8% of the fruit was severely affected. After 25 weeks CI incidence and severity increased significantly and affected 33.8% of the fruit (Schirra and Cohen 1999).

Development of decay in stored oranges tends also to increase as storage time and temperature increases. For example, 'Ambersweet' orange fruit held for 2 weeks at 1 and 4°C plus 7 days at 20°C did not show any evidence of decay. However, after 14 days at 20°C, fruit previously stored at 4 and 1°C showed 2.8 and 0.9% decay, respectively, which increased to 5.5 and 3.4% after 21 days at 20°C (Hearn 1990). Decay in 'Olinda' oranges stored at 3°C increased from 2.0% after 8 weeks of storage to 6.0% after 25 weeks (Schirra and Cohen 1999). 'Valencia' oranges stored at 4°C showed a significant increase in decay, and after 6 months about 24% of the fruit had decay (Erkan et al. 2005).

Hot-water or hot-air treatments have been successfully used to alleviate CI symptoms in oranges stored for extended periods at chilling temperatures. These treatments may also significantly reduce the incidence of decay during storage at nonchilling temperatures. For example, hot-water dipping treatment at 5°C for 2 minutes before storage of

'Washington navel' oranges for 5 weeks at 1°C reduced the development of CI during storage for 1 week at 20°C (Wild 1993). Likewise, a 3-minute dip treatment at 52°C reduced the development of CI symptoms during storage for 2 months at 8°C followed by 1 week at 20°C, compared to fruit dipped in water at 25°C (Schirra and Mulas 1995b). A pre-storage hot-water treatment at 48°C for 12 hours and a curing treatment at 53°C for 6 hours were also effective in reducing CI and decay in 'Valencia' oranges stored at 4°C for 6 months, as no decay was observed in cured or hot-water dipped fruit after 4 months of storage at 4°C (Erkan et al. 2005). 'Shamouti' oranges stored at 5°C developed approximately 50% decay after 6 weeks of storage. However, a pre-storage hot-water brushing treatment at 56°C for 20 seconds followed by storage for 6 weeks at 5°C plus 1 week at 20°C reduced development of decay by 55%, without damaging the fruit (Porat et al. 2000a). Intermittent warming of the fruit (3 weeks at 3°C followed by 2 weeks at 15°C for 25 days) during storage at chilling temperatures also alleviated CI symptoms in 'Olinda' oranges compared to continuous storage at 3°C. CI development was delayed by 10 weeks and resistance increased in intermittently warmed fruit, compared to fruit stored continuously at 3°C (Schirra and Cohen 1999).

Compared to fruit dipped in water at 25°C, hot-water dip for 3 minutes at 52°C followed by storage for 2 months at 8°C plus 1 week at 20°C reduced by four times the incidence of decay in 'Tarocco' oranges and delayed by 2 weeks mold appearance (Schirra and Mulas 1995b). Curing at 33°C for 65 hours also reduced the incidence decay in oranges stored at 4°C for 2 months followed by 7 days at 20°C (Plaza et al. 2003). Likewise, exposure of 'Tarocco' oranges to 32 or 36°C for 2 or 3 days decreased the decay percentage after 60 days of storage at 8°C, whereas fruits stored continuously at 8°C developed 8–20% decay (Lanza et al. 2000). However, exposure of oranges to a hot-air treatment at 37°C for 48 hours resulted in increased weight loss; decreased juice yield, firmness, and ascorbic acid content; and had a negative effect on fruit taste and flavor (Schirra et al. 2004). Therefore, hot-air or -water treatments may affect the visual and eating quality of oranges when the temperature exceeds a certain threshold or exposure duration. Navel oranges heated at either 46°C for 4.5 hours or at 50°C for 2 hours, or immersed for 3 hours at 46°C, showed an increase in chroma values and a shift from orange toward orange-yellow, compared to nonheated fruit, most likely due to synthesis of carotenoids in the peel during 4 weeks of storage at 7°C and 1 week at 23°C (Shellie and Mangan 1998). Although no significant differences were found in the weight loss, juice percentage, acidity, soluble solids content, soluble solids content-to-acidity ratio, and flavedo color of 'Valencia' oranges heated at 46, 47, or 50°C, the flavor of oranges exposed to 47 or 50°C was inferior to that of oranges exposed at 46°C. Longer exposure times (4 hours) resulted in poorer external appearance (Shellie and Mangan 1994). In addition, a 5-hour high-temperature forced-air treatment (35°C ramping to 48.5°C during a period of 200 minutes and held until fruit temperature reaches 47.2°C for 2 more minutes) applied to 'Valencia' and navel oranges resulted in decreased volatile compounds and flavor quality (Obenland et al. 1999). Immersing navel oranges in water for 3 hours at 46°C also resulted in increased mass loss and decay and decreased flavor because the direct contact of the fruit with the hot water might have caused irreversible damage to the flavedo tissue and oil glands (Shellie and Mangan 1998). Therefore, to maintain a good quality during subsequent storage, 'Valencia' oranges should not be exposed to hot air at 46°C for more than 230 minutes (Shellie and Mangan 1994), and navel oranges should not be exposed to hot water at temperatures higher than 46°C for more than a few hours (Shellie and Mangan 1998).

Weight loss is also affected by storage time and temperature. For example, 'Lanes Late' oranges stored at −1 and 3°C showed a weight loss of 0.09 and 1.6% after 20 and 30 days, respectively. However, upon transfer to 22°C for 30 days, weight loss increased to 16% (Henriod et al. 2005). Weight loss of oranges stored for 16 days at 1°C ranged from 1.56 to 2.34% and significantly increased to 4.71–6.37% upon transfer to 8°C for 3 weeks plus 1 week at 20°C (Schirra et al. 2004). 'Valencia' oranges stored at 4°C showed increased weight loss during storage, and after 6 months the fruit had lost 4.98% of the initial weight (Erkan et al. 2005). Increased weight loss was observed in oranges exposed to 33°C for 24–72 hours followed by storage for 2 months at 4°C (Plaza et al. 2003). Likewise, weight loss in 'Tarocco' oranges exposed to 32 or 36°C for 2 or 3 days followed by storage at 8°C was significantly higher than in fruit stored continuously at 8°C (Lanza et al. 2000). 'Lanes Late' oranges stored at 1 or 5°C plus 21 days at 20°C in high- or low-humidity levels lost approximately 3 and 13% of their initial weight after 77 days, respectively (Henriod 2006). After 20 days, weight loss in oranges stored at 12, 20, and 30°C and 45% relative humidity reached approximately 2.5, 3, and 13%, respectively, whereas weight loss in fruit stored at the same temperatures but 95% relative humidity was approximately four times lower (Alférez et al. 2003).

Reduced humidity during storage not only results in loss of moisture and fruit dehydration but may also lead to peel damage. Rind breakdown was observed in 'Navelina' and 'Navelate' oranges with weight loss greater than 2% that were transferred from low (45%) to high-humidity (95%) storage. The symptoms of rind breakdown were initially depressed or irregular areas scattered at the equatorial part of the fruit, and depressed flavedo areas became evident within 3–7 days after transfer of fruit from 45 to 95% humidity. Several days after, those areas with symptoms of rind breakdown became dried and discolored and turned progressively brown and black (Alférez et al. 2003). In 'Shamouti' oranges a similar flavedo breakdown called noxan was also identified in fruit stored at high temperature and low humidity (20°C and 75–80% humidity). Fruit stored at 5 or 6°C had a lower incidence of noxan than fruit stored at 20°C, and fruit stored at 5°C and 90% humidity showed higher noxan than did packed fruit (100% humidity) at the same temperature. Therefore, decreasing the temperature and increasing the humidity levels around the fruit reduced the weight loss, maintained the fruit turgidity, and reduced noxan incidence (Peretz et al. 2001; Yehoshua et al. 2001).

Removal of natural epicuticular wax in 'Valencia' oranges during normal packinghouse washing and brushing operations, combined with low-humidity storage, also resulted in higher weight loss, and consequently accelerated stem-end rind breakdown (Albrigo 1972). Therefore, to minimize loss of moisture and fruit peel dissection, wax coatings are generally applied to the fruit after washing and prior to storage as a standard packinghouse procedure. In fact, wax coatings applied to 'Valencia' oranges prior to storage contributed to reduced loss in moisture and peel shrinkage, and increased peel glossiness (Hagenmaier 2000). Waxing minimized loss of typical orange color and peel glossiness but reduced total phenol content (Moussaid et al. 2004).

Temperature also affects the composition of oranges during the postharvest period. For example, after holding oranges at 1°C for 16 days followed by a 3-week storage at 8°C plus 1 week at 20°C, changes in soluble solids and ascorbic acid content were not significant, but a reduction in fruit acidity was observed after storage (Schirra et al. 2004). Likewise, initial acid content of 'Olinda' oranges stored at 3°C decreased by approximately 30% after 25 weeks. However, an increase of almost 20% was observed in the soluble solids content, compared to initial values (Schirra and Cohen 1999). Conversely, when oranges were held at 4°C, citric acid, soluble solids, and ascorbic acid contents decreased during storage. Therefore, after 6 months, the initial contents of citric acid, soluble solids, and ascorbic acid were reduced by 25.8, 8.6, and 26.5%, respectively (Erkan et al. 2005). Soluble solids, acidity, and anthocyanin content of the juice increased during storage of 'Tarocco' oranges at 8°C, whereas pH tended to decrease (Lanza et al. 2000). During storage of blood oranges at 8 or 22°C, acidity and ascorbic acid contents decreased, and total soluble solids increased, resulting in an increase in the maturity index during storage. After 40 days of storage at 8°C, anthocyanin content of 'Tarocco' oranges increased by about 500%, but only by 19% in 'Mouro' fruit. In fruit stored at 22°C, anthocyanin content remained unchanged or decreased (Rapisarda et al. 2001). Likewise, long storage periods (75 days) at 4°C induced anthocyanin accumulation in the juice of red oranges, and the pigment concentration was eight times higher than in fruit held at 25°C (Piero et al. 2005). Exposure of oranges to 33°C for 24–72 hours followed by storage for 2 months at 4°C reduced the citric acid content and the soluble solids content-to-acidity ratio of orange fruit (Plaza et al. 2003). Likewise, exposing navel oranges to forced air at 46°C for 4.5 hours resulted in a significant reduction in acidity and juice yield, and in a significant increase in soluble solids content-to-acidity ratio, compared to nonheated fruit (Shellie and Mangan 1998).

Time and Temperature Effects on the Visual Quality of 'Valencia' Oranges

'Valencia' oranges shown in Figures 1.9–1.16 were harvested at the legal maturity standard for Florida from a commercial operation in Fort Pierce, Florida, during the spring season (i.e., April). Promptly after harvest (within 6 hours), fresh orange was degreened according to the recommended procedures for degreening Florida citrus (Ritenour et al. 2003a; Wardowski et al. 2006). Subsequently, fruits were washed with water, but not waxed, and stored at five different temperatures (0.5 ± 0.3°C, 5.0 ± 0.2°C, 9.4 ± 0.4°C, 14.40 ± 0.4°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Major effects of temperature on visual quality of 'Valencia' oranges during storage are related to changes in peel glossiness, loss of moisture and dryness, aged appearance, and development of decay.

'Valencia' oranges stored at 0°C maintained acceptable visual quality during 72 days, but after that time slight mycelium growth is evident at the stem-end of the fruit (Figure 1.9). Although oranges stored at 0°C show no evidence of any typical peel pitting associated with CI during storage, after 42–52 days some fruit appears old and dry, showing sunken and discolored lesions on the flavedo around the stem-end and rind brown-staining, upon transfer to 20°C for 2 additional days (Figure 1.10).

When stored at 5°C, visual quality of 'Valencia' oranges deteriorates quickly. After 20 days of storage, stem-end breakdown becomes apparent and aggravates with storage time (Figure 1.11). After 52 days the peel around the stem-end appears dry and sunken and develops a rusty coloration.

Stem-end decay develops after 32 days in 'Valencia' oranges stored at 10 and 15°C, and after 52 days mycelium growth is evident in fruit stored at both temperatures (Figures 1.12 and 1.13). Simultaneously the fruit develops a dry, aged, and unpleasant appearance. However, dryness in oranges stored at 15°C is more pronounced than in fruit stored at 10°C.

Deterioration occurs quickly in 'Valencia' oranges held at 20°C due to aging of the fruit. Desiccation and peel shriveling becomes evident after only 10 days of storage, increases to moderate levels after 20 days, and after 52 days severe peel desiccation and brown-staining affect most of the fruit surface (Figures 1.14 and 1.15). Simultaneously, after 20 days mycelium growth becomes evident at the stem-end of the fruit, whereas after 32 days the entire fruit is severely affected by decay (Figures 1.15 and 1.16).

In general, postharvest life of 'Valencia' oranges is limited by changes in peel appearance and development of decay. Oranges stored at 0°C maintain good visual quality for a longer period than fruit stored at higher temperatures (42 days). 'Valencia' oranges stored at 5, 10, or 15°C retain acceptable visual quality during 20 days, whereas visual quality of oranges stored at 20°C is no longer acceptable after 10 days.

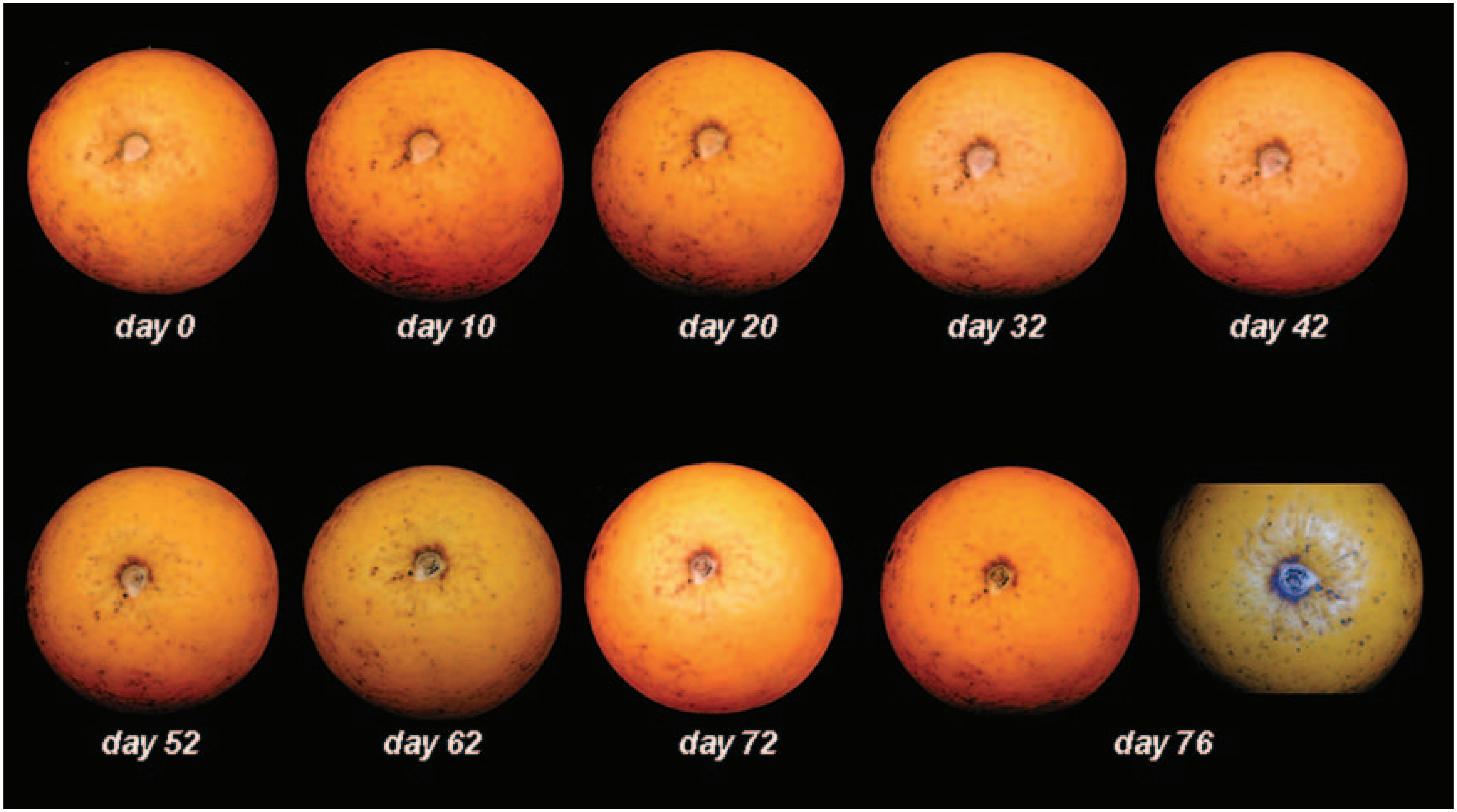
day 0
day 10
day 20
day 32
day 42
day 52
day 62
day 72
day 76

Figure 1.9. Appearance of 'Valencia' orange stored for 76 days at 0°C. After 76 days slight mycelium growth is evident at the blossom-end of the fruit.

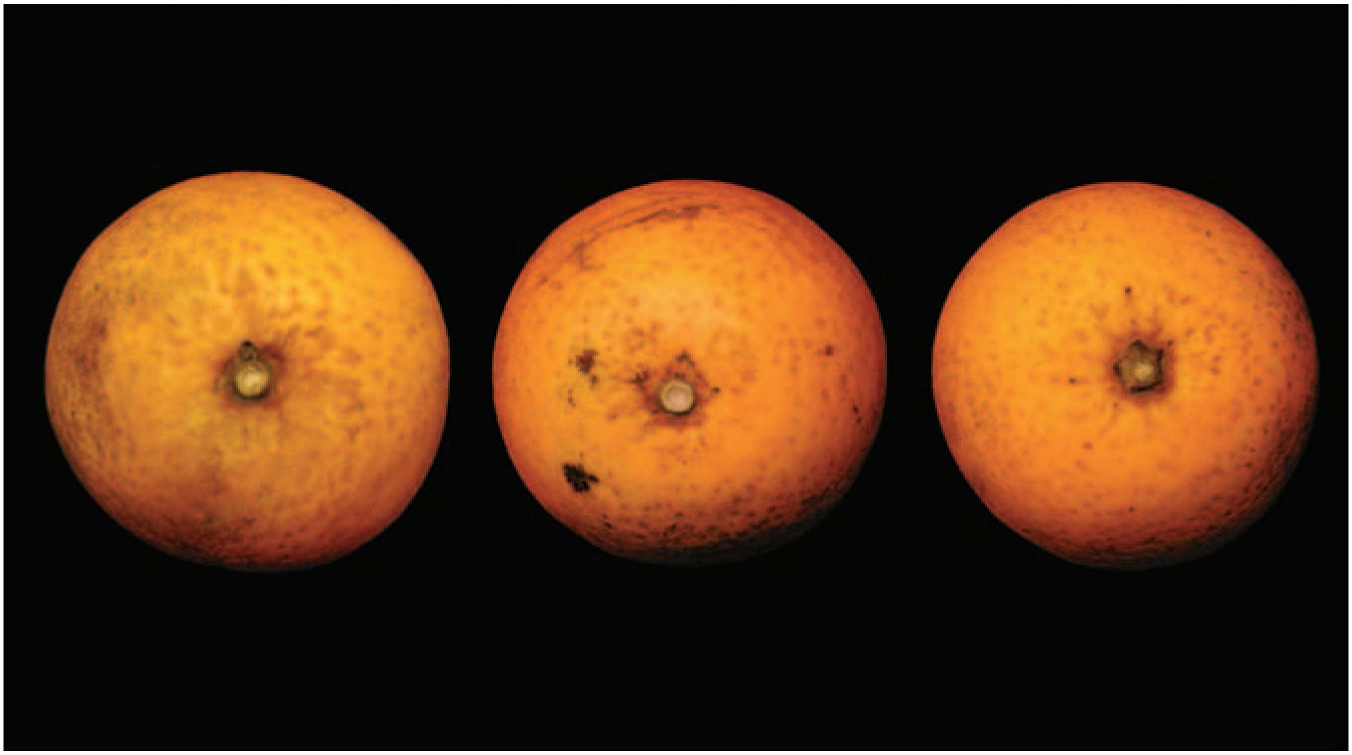

Figure 1.10. Appearance of 'Valencia' orange after storage for 42 (left) and 52 days (center and right) at 0°C followed by 2 days at 20°C. No signs of CI are noticeable, but the fruit appears dry and aged.

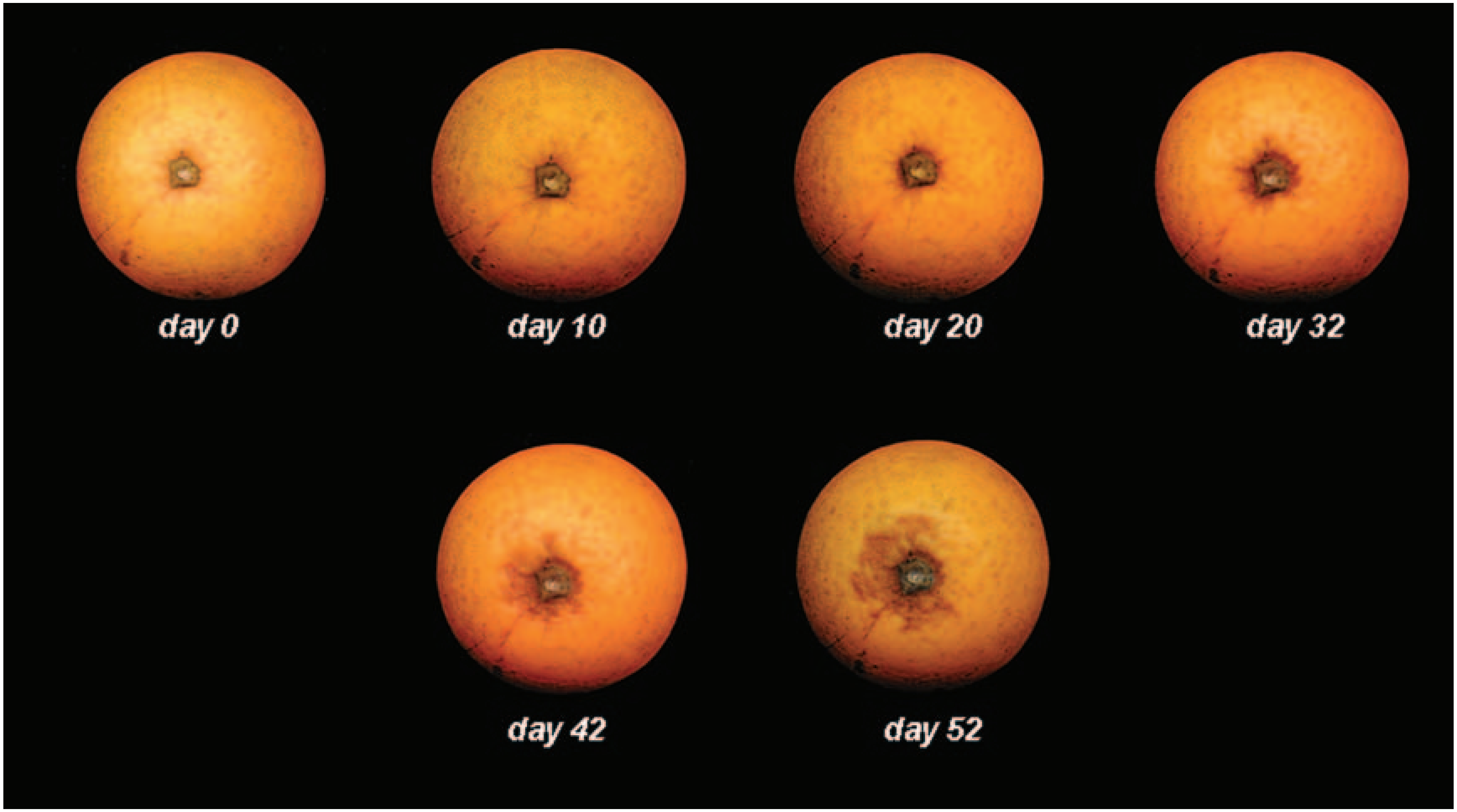
day 0
day 10
day 20
day 32
day 42
day 52

Figure 1.11. Appearance of 'Valencia' orange stored for 52 days at 5°C. After 20 days slight stem-end breakdown develops and increases with storage time. After 52 days the color of the peel around the stem-end develops a rusty coloration and appears dry.

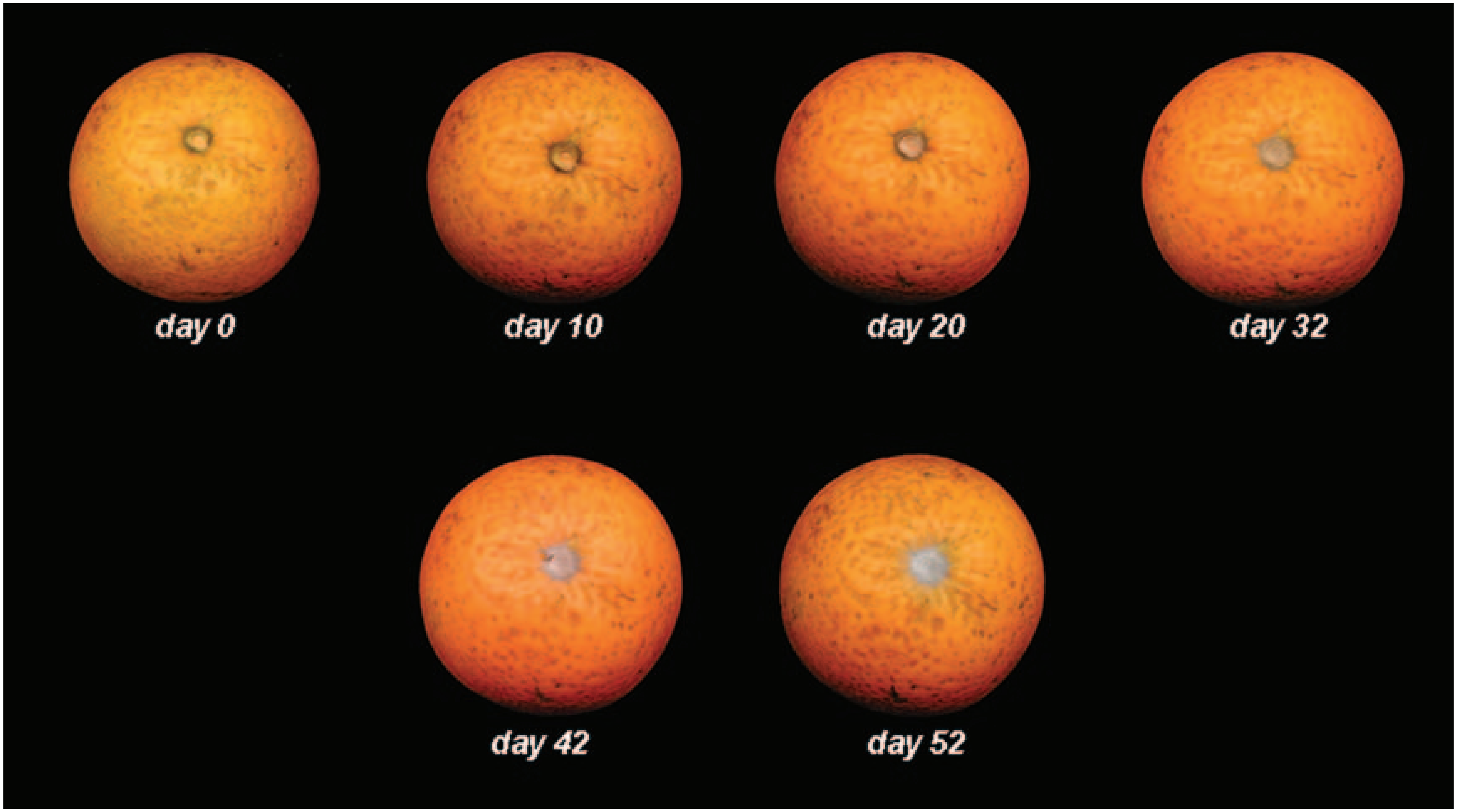
day 0
day 10
day 20
day 32
day 42
day 52

Figure 1.12. Appearance of 'Valencia' orange stored for 52 days at 10°C. After 20 days stem-end decay develops and increases with storage time. After 52 days decay is evident at the stem-end of the fruit.

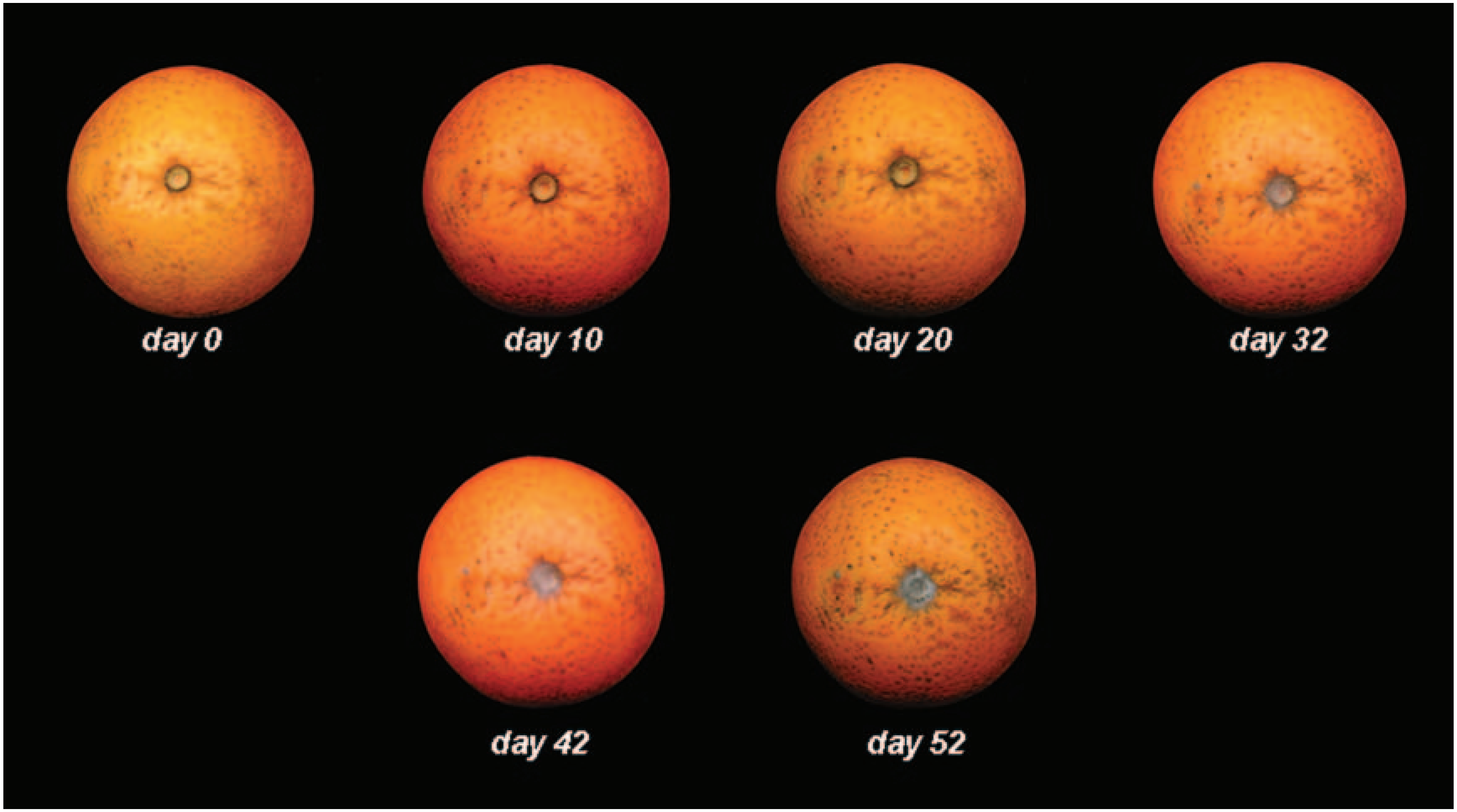
day 0
day 10
day 20
day 32
day 42
day 52

Figure 1.13. Appearance of 'Valencia' orange stored for 52 days at 15°C. After 20 days slight stem-end decay and peel desiccation develops and increases with storage time. After 52 days the peel of the fruit appears dry and decay is evident at the stem-end.

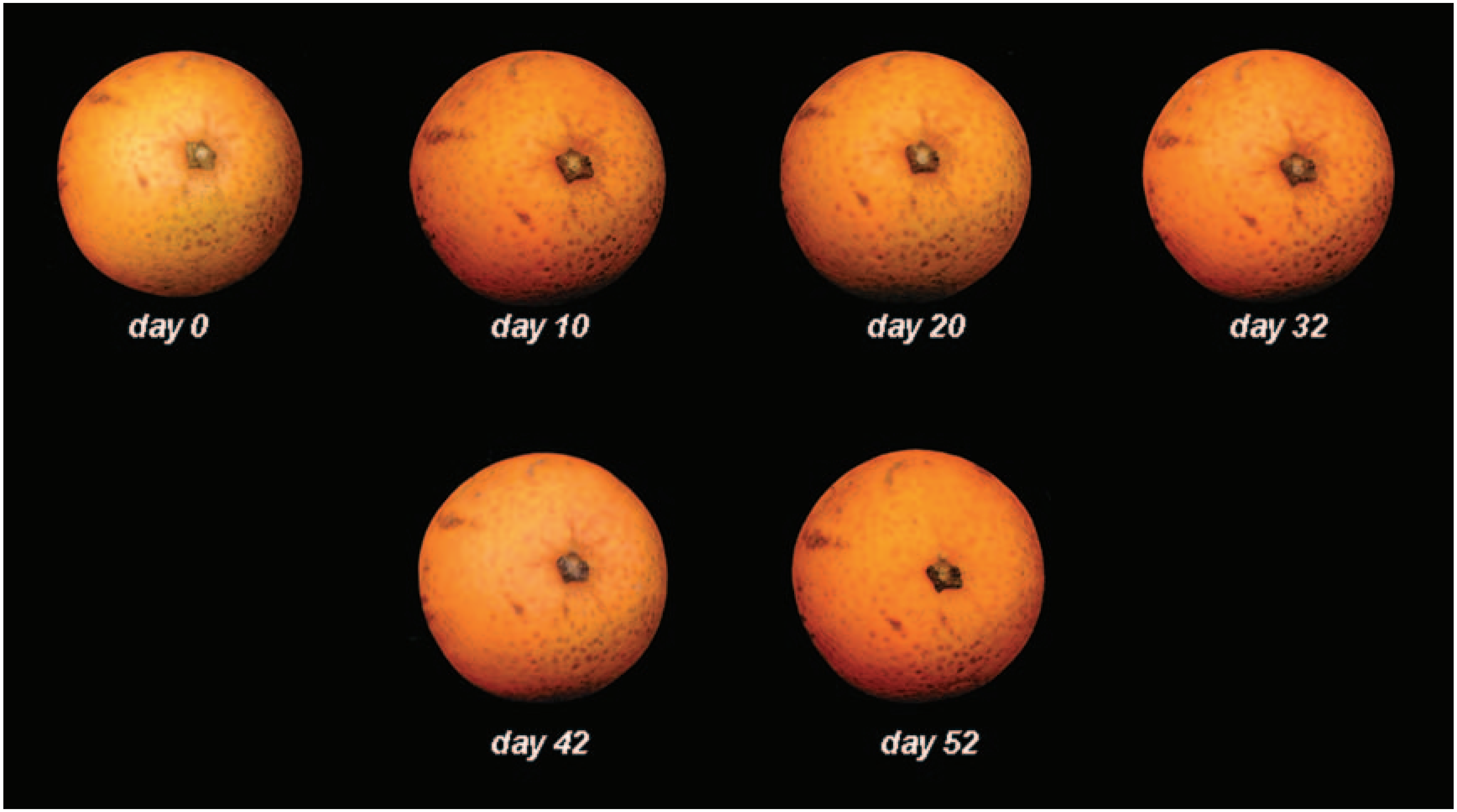
day 0
day 10
day 20
day 32
day 42
day 52

Figure 1.14. Appearance of ‘Valencia’ orange stored for 52 days at 20°C. After approximately 10 days peel desiccation develops and increases with storage time. After 52 days the peel of the fruit appears very dry and shriveled.

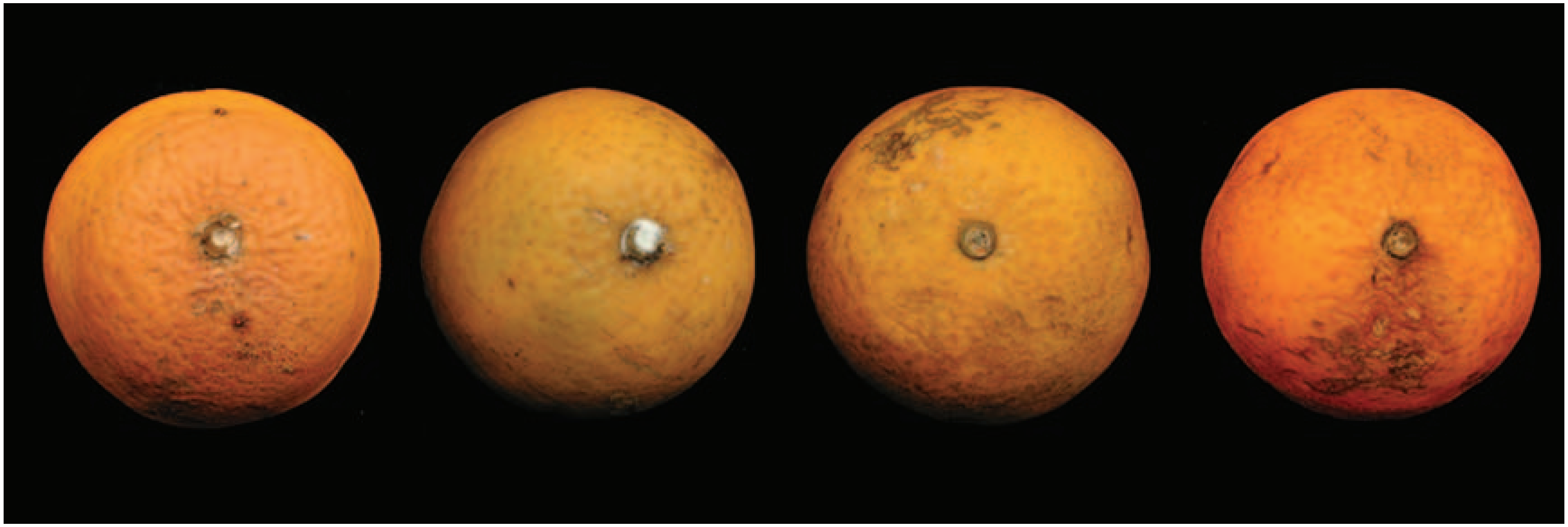

Figure 1.15. After 20 days (left) 'Valencia' orange stored at 20°C develops moderated decay and shriveling, and after 52 days (right) shriveling is objectionable and affects the entire peel of the fruit.

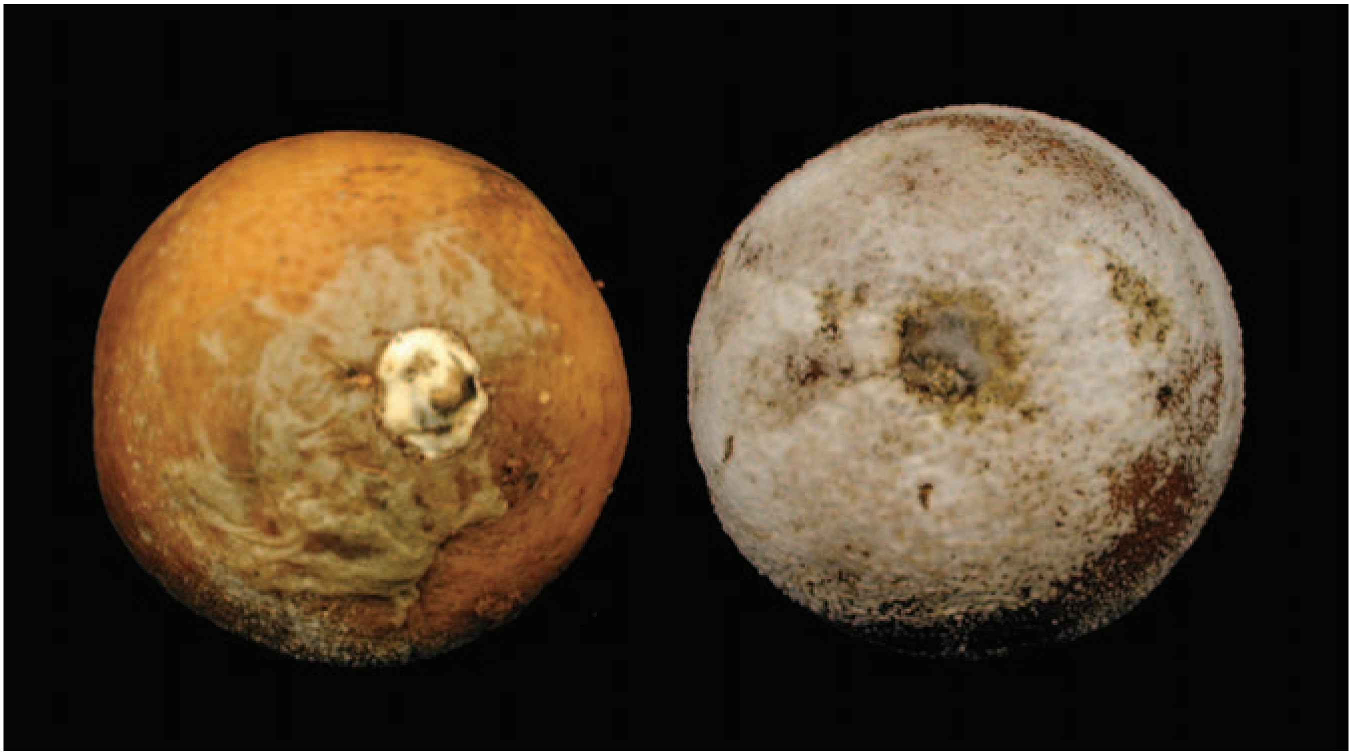

Figure 1.16. Severe decay in 'Valencia' orange stored for 32 days at 20°C.

MANDARIN

Scientific Name: *Citrus reticulata*
Family: Rutaceae

Quality Characteristics

Mandarin is a diverse group of citrus fruit that includes the worldwide varieties of 'Satsumas' (*Citus unshiu*), Mediterranean mandarins (*Citrus deliciosa*), king mandarins (*Citrus nobilis*), and the common mandarins (*Citrus reticulata*) (Burns 2004b). The common mandarins are in fact tangerines, which are a subgroup of the mandarins. Varieties of tangerines include 'Clementine,' 'Dancy,' 'Fairchild,' 'Fallglo,' 'Honey,' and 'Sunburst.' The primary difference between other mandarins and tangerines is the color of the peel. The tangerine has a darker reddish-orange peel and the mandarin has a lighter orange color. In addition, 'Clementine' and 'Satsuma' mandarins are easier to peel, are seedless, and have a sweeter taste than tangerines (Campbell et al. 2004; Cooper and Chapot 1977; Ebel et al. 2004; Muramatsu et al. 1999). 'Murcott,' or 'Honey,' tangerines have a deep reddish-orange peel color that may be yellow-orange when winters are warmer. The peel is smooth and the flesh is tender, very sweet and juicy, and has a rich flavor and an orange color (Borges and Pio 2003; Cohen et al. 1990; Stephen and Jackson 2003).

Overall, a high-quality mandarin should have a turgid and firm, deep orange-red peel, which should be easily removed from the flesh by hand. The flesh should be juicy and contain few or no seeds (Burns 2004b). According to regulations set forth by the Commission of the European Communities, the optimum maturity mandarins should have a minimum juice content of 33–40% and the color should be typical of the variety on at least one-third of the surface of the fruit (Commission of the European Communities 2002). In the United States, maturity standards require that mandarins have a minimum soluble solids content-to-acidity ratio of 6.5 or higher and have a yellow, orange, or reddish color on at least 50–75% of the peel surface (Arpaia and Kader 2006; Burns 2004b). Depending on the cultivar, freshly harvested mandarin acidity ranged from 0.73 to 0.8%, pH from 3.24 to 3.65, and soluble solids content from 10.5 to 10.8% (Pérez-López and Carbonell-Barrachina 2005). For most supermarkets, external quality standards require that premium mandarins ('Clementine,' 'Satsuma,' or tangerine) be orange, unblemished, and large. In a consumer perspective, mandarins should have a relatively long post-purchase life (i.e., at least 31 days), should not be packed, and should display a high vitamin C content label (Campbell et al. 2006). Furthermore, seedless mandarins seem to be preferred over seeded fruit, while color and size are considered less important purchasing decision factors (Campbell et al. 2004). However, any green color on the fruit surface strongly reduces consumer preferences (Ebel et al. 2004). 'Satsuma' mandarins with soluble solids content-to-acidity ratio of 10 : 1 and no green color were also preferred by most consumers (Ebel et al. 2004). Internal fruit quality, such as flavor and sweetness, is largely dependent on the amount of sugars and acids present in the fruit, and for most consumers was also considered an important quality factor, particularly fruit sweetness (Poole and Baron 1996).

In general, as mandarin fruit matures soluble solids content increases and acidity decreases, resulting in an increased soluble solids content-to-acidity ratio. At the same time, peel softens due to a decrease in cell-wall polysaccharides (Muramatsu et al. 1999) and color changes from green to yellow (Ebel et al. 2004). During periods of water stress, the soluble solids content of the fruit may increase, whereas acidity may either decrease or increase (Moon and Mizutani 2002). High temperatures during development in the tree may advance fruit maturity and contribute to a decrease in total acidity, citric and malic acids (Marsh et al. 1999). Conversely, total sugars—sucrose, glucose, and fructose—increase during fruit development (Richardson et al. 1997). Mandarin fruit contains on average 85% water, 13% carbohydrates, 0.8% proteins, and 1.8% fiber (USDA 2006). Mandarin fruit may contain between 14 and 54 mg of vitamin C and 155 µg of β-carotene per 100 g of fresh fruit depending on the cultivar, stage of maturity, and environmental factors during development in the field as well as postharvest handling conditions (Nagy 1980; USDA 2006).

Optimum Postharvest Handling Conditions

Prompt pre-cooling of mandarins after harvest helps to prevent peel disorders and development of decay during storage. A cooling delay of 12–24 hours or longer significantly increased the incidence of postharvest pitting in

'Fallglo' tangerines (Dou and Ismail 2000). After precooling, mandarins can be stored at between 5 and 8°C with 95% relative humidity for 4 weeks. If stored at temperatures lower than 5°C, CI may develop depending on the variety, temperature, and duration of storage. 'Fallglo' tangerines can be stored, however, at 4°C without the risk of developing CI (Dou and Ismail 2000). Symptoms of CI in mandarin cultivars are characterized by peel pitting and brown discoloration, followed by increased susceptibility to decay (Burns 2004b).

Although some mandarin cultivars such as 'Fallglo' tangerines have the ability to degreen during postharvest without continued external ethylene exposure (Dou and Ismail 2000), in general, prior to washing and waxing, green mandarins are exposed to ethylene (1–5 μL/L) for periods of 12 hours to 3 days at temperatures between 28 and 29°C and 95% relative humidity (Ritenour et al. 2003a; Burns 2004b; Wardowski et al. 2006). Cold shock treatments prior to storage have also been shown to reduce chlorophyll and increase carotenoid content in 'Nules Clementine' mandarins to a similar extent as commercial ethylene degreening. In addition, fruit exposed to cold shock had a similar rind color and was firmer and less wilted than ethylene-degreened fruit (Barry and Wyk 2006).

Temperature Effects on Quality

Although not all mandarins are sensitive to chilling temperatures, some cultivars may develop symptoms of CI when stored at temperatures below 5°C. The severity of the symptoms increases with the length of exposure to chilling temperatures and is usually aggravated upon transfer of the fruit to ambient temperatures. Common symptoms of CI in mandarins include the development of brown pit-like depressions and bronze nondepressed areas or scald in the flavedo (Lafuente et al. 2005; Sala 1998). After 3 weeks at 0°C, 'Emperor' mandarins developed symptoms of CI, which aggravated with exposure time to chilling temperature (Yuen et al. 1995). Although no symptoms of CI developed in 'Clemenules' and 'Clementine' mandarins after storage at 2.5°C, 'Nova' and 'Fortune' fruit showed signs of CI after 2 weeks of storage, and the symptoms increased significantly after 8 weeks (Sala 1998). 'Fortune' mandarins stored at 2°C developed pitting and rind staining after 14 days of storage (Gonzalez-Aguilar et al. 1997; Holland et al. 2002). The symptoms of CI in 'Fortune' mandarins stored for 15–30 days at 5–6°C appeared in the form of discolored, small pitted areas and skin depressions irregularly distributed over the fruit surface (Schirra and D'Hallewin 1997). However, no CI was observed in the flavedo of 'Fortune' mandarins stored at 12°C (Gonzalez-Aguilar et al. 1997; Holland et al. 2002).

Symptoms of CI such as scald and rind pitting were reduced by wrapping 'Malvasio' mandarins in plastic films prior to storage for 6 or 12 weeks at 4°C plus 1 week at 20°C (D'Aquino et al. 2001). Heat treatments have also been used to delay and alleviate symptoms of CI following low-temperature storage. For example, compared to untreated fruit, 'Fortune' mandarins dipped in hot water between 50 and 54°C showed a reduction in CI and decay during cold storage for 30 days at 5–6°C plus 3 additional days at 20°C (Schirra and D'Hallewin 1997). Likewise, hot-water dips at 52°C for 3 minutes reduced the severity of CI and the incidence of decay in 'Fortune' mandarins (Schirra and Mulas 1995a). Exposure of 'Fortune' mandarins at 37°C for 3 days also increased the tolerance to CI during storage at 2°C (Holland et al. 2002).

Although heat treatments may be used to reduce CI during cold storage, temperatures that are too high combined with exposure times that are too long may cause heat damage and loss of fruit quality. For example, 'Fortune' mandarins dipped in hot water for 3 minutes at temperatures between 54 and 58°C showed heat damage such as rind browning and scalding. Heat damage symptoms increased with increasing treatment temperature and aggravated during subsequent storage at 5–6°C. After 30 days of storage, 10, 70, and 100% of the fruit dipped in hot water at 54, 56, and 58°C, respectively, showed moderate to severe heat damage. Furthermore, the taste of fruit dipped in water at 58°C was considered poor, and the peel was corky, thin, and appeared dull. Dipping the fruit in hot water also contributed to increased weight loss during subsequent storage due to cellular breakdown, loss of membrane integrity, and removal of natural epicuticular waxes. Thus, to maintain the internal quality of the fruit, the maximum water temperature for heat treatment of 'Fortune' mandarins should not exceed 54°C for 3 minutes (Schirra and D'Hallewin 1997).

Postharvest peel pitting is a disorder that may develop when waxed mandarins are stored at above-optimum temperatures (see also "Grapefruit" section). The disorder is characterized by scattered collapse of the flavedo that results in necrosis of the cells within and enveloping the oil glands. In severe cases, damage may occur in epidermal and hypodermal cells above collapsed oil glands and adjacent vascular tissues, but cells between oil glands are often intact (Petracek et al. 1998). Initial symptoms of postharvest peel pitting appeared in waxed 'Fallglo' tangerines 2 or 6 days after wax application in fruit stored at 15.5 or 26.5°C, respectively. Pitting developed first at the stem-end but became more evenly distributed over the fruit surface after 28 days of storage at 15.5°C. Pitting was less severe and less frequent in fruit stored at 15.5 than at 26.5°C. Nonwaxed fruit stored at 4.5 or 15.5°C did not develop pitting, but approximately 10% of the nonwaxed fruit stored at 26.5°C showed pitting after 20 days of storage (Petracek et al. 1998).

In general, pitted 'Fallglo' tangerines showed a higher release of volatiles, mainly limonene, from the oil glands than nonpitted fruit. This was attributed to the breakdown of oil glands in pitted fruit caused by storage at high temperatures (2°C) (Dou 2003). Alteration of water status of the peel was reported to also have a major effect on the development of pitting in 'Fallglo' tangerines. In fact, a high correlation was found between weight loss and postharvest peel pitting in 'Fallglo' tangerines. When the fruit was stored at 20°C, a 2-hour exposure to low humidity (30%) was sufficient to induce peel pitting in tangerines after transfer to high humidity (90%) (Alférez et al. 2005). In addition, damage of the epicuticular wax structure may result in increased flavedo water permeability and water loss and influence the development of peel pitting during storage (Sala 2000).

Mandarins may also develop juice-vesicle disorders during storage, which cause granulation and dehydration of the fruit sections. In fruit affected by granulation, the juice vesicles become hard at first and then the inner cells collapse, resulting in an empty crystalline-like cavity. Dehydration begins with a slight shrinkage followed by complete collapse of the affected vesicles due to loss of fluids. The term "section-drying" refers to the condition where vesicles within a segment appear either dehydrated, collapsed, or granulated. The development of the disorder varies with the season of harvest, cultivar, harvest date, and length of storage (Peiris et al. 1998). In most cases, granulated fruits are larger in size and have lower juice content, total soluble solids, acidity, and ascorbic acid and phenolic contents than normal fruit. Compared to other citrus cultivars, 'Kaula' mandarins had the highest incidence of granulation (62.5%) (Sharma et al. 2006).

Granulation not only affects the overall firmness of the fruit but also the fruit flesh texture. Firmness of the flesh is an important characteristic because it influences the mouth feel of citrus. Other than changes in the juice content of the vesicles, firmness of the flesh appeared to be highly correlated with the cell-wall polysaccharide content and composition. 'Satsuma' mandarins were reported to have the softest texture compared to other citrus cultivars (Muramatsu et al. 1996). Firmness of the fruit generally decreased with increasing storage time and temperature. For example, firmness of 'Clemenules' mandarins stored for 21 days at 20°C decreased by 28% after the fruits were transferred to 18°C for 7 days (Plaza et al. 2004).

Decay is probably one of the main causes of mandarin losses during the postharvest period. Decay may develop very quickly if fruit is handled under inadequate conditions. For example, decay increased during storage of 'Malvasio' mandarins and after 12 weeks at 4°C, 3% of the fruit was affected. After transfer to 20°C for 1 week decay increased, and only 59% of the fruit was suitable for sale (D'Aquino et al. 2001). After 45 days of storage at 12°C, approximately 15% of 'Fortune' mandarins showed signs of decay, whereas only 5% of the fruit stored at 2°C was affected (Gonzalez-Aguilar et al. 1997). After 7 days, 100% of the fruit of 'Nules' mandarins stored at ambient temperatures (18–20°C) developed decay (Pérez et al. 2005), whereas 'Minneola' and 'Sunburst' developed 16 and 36% decay after storage for 2 weeks at 22°C (Dou et al. 2004).

Intermittent curing (18 hours at 38°C followed by 6 hours at 20°C plus 18 hours at 38°C) followed by either cold storage at 5°C or warm storage at 20°C significantly reduced decay in 'Hernandina' mandarins compared to continuous storage at 5 or 20°C. After 9 days, fruit stored continuously at 20°C showed the highest amount of decay (25%), followed by fruit stored at 5°C (5%), cured fruit stored at 20°C (4%), and cured fruit stored at 5°C (2%) (Pérez et al. 2005). Other curing regimens were also effective in controlling green and blue mold incidences in 'Clemenules' mandarins (Plaza et al. 2004). Likewise, water dipping treatments at 52°C for 2 minutes, 55°C for 1 minute, or 60°C for 20 seconds were also effective in reducing the amount of decay in 'Satsuma' mandarins without impairing fruit quality (Hong et al. 2007).

Weight loss in mandarin fruit increases with increasing storage time and temperature. For example, after 45 days 'Fortune' mandarins stored at 2°C had less weight loss (3–5%) than fruit stored at 12°C (12–15%). After 6 weeks at 4°C, weight loss of 'Malvasio' mandarins reached 6.7% and increased to 13.3% after 12 weeks. When the fruit were transferred to 20°C for 1 week, weight loss significantly increased and attained 17.8% (D'Aquino et al. 2001). Weight loss in 'Mor' mandarins stored at 5°C reached approximately 8.5% after 4 weeks plus 5 additional days at 20°C (Porat et al. 2005). Likewise, after 21 days at 5°C weight loss of 'Satsuma' mandarins attained 5.5%, and increasing the storage temperature to 18°C increased the fruit weight loss to approximately 10% after 7 days of storage (Hong et al. 2007). When weight loss of 'Mor' mandarins reached 4.8% the fruit looked shriveled and had a dull color and a poor visual appearance (Porat et al. 2005). 'Nules' mandarins stored at ambient temperature (18–20°C) showed a 0.97% reduction in initial weight after 2 days, and after 7 days weight loss had increased to 1.75%. Furthermore, intermittently warmed fruit (two cycles of 18 hours at 38°C) subsequently stored at ambient temperature for 1 week showed much higher weight loss (4.75%) than nonwarmed fruit (Pérez et al. 2005). A maximum weight loss of less than 4% was suggested for 'Satsuma' mandarins before the fruit became unacceptable for sale. Fruit stored at 30°C and low relative humidity (65%) lost more than 4% weight and thus had unacceptable levels of dehydration and shriveled, dull colored, and soft skin (Burdon et al. 2007).

Waxes, coatings, or film wraps are used to improve fruit peel color and gloss and to help reduce loss of moisture and shrinkage during postharvest handling. However, waxes that restrict gas exchanges through the peel may cause the development of off-flavors and fruit deterioration (Hagenmaier 2002; Hagenmaier and Shaw 2002; Porat et al. 2005). 'Murcott' tangerines are highly susceptible to anaerobic conditions and may deteriorate rapidly when exposed to such conditions. Although postharvest waxing of 'Murcott' tangerines reduced weight loss, the taste and flavor became unacceptable and fruit quality was impaired (Cohen et al. 1990; Hagenmaier 2002; Shi et al. 2005). Waxing of 'Fallglo' tangerines with a commercial shellac-based wax delayed fruit color changes and slightly reduced water loss during storage at 4.5 or 15.5°C for 15 days, but it can promote the development of postharvest pitting (Petracek and Montalvo 1997). Likewise, postharvest applications of chitosan coatings to 'Clemenules' mandarins delayed peel senescence without affecting internal fruit quality, decreased softness and the water absorption capacity of the peel, and decreased by 65% the incidence of water spot (small cracks around the stem-end that develop into brown spots) (Fornes et al. 2005). Mandarins treated with wax and resin coatings may be stored for 7 days at 5°C without their quality being impaired (Hagenmaier 2002). Film-packed ‘Malvasio’ mandarins stored for 6–12 weeks at 4°C plus 1 week at 20°C showed less weight loss, but in some cases the high humidity created inside the package resulted in increased pathogen growth (D’Aquino et al. 2001).

Mandarin fruit composition changes during postharvest and is greatly affected by storage time and temperature. For example, sucrose, glucose, fructose, and starch contents decreased during storage of ‘Fortune’ mandarins at 2 or 12°C, but the decrease was significantly higher in fruit stored at higher temperature. However, heating the fruit for 3 days at 37°C avoided the decline of sucrose during subsequent storage at 2°C (Holland et al. 2002). Storage of ‘Malvasio’ mandarins for 12 weeks at 4°C plus 1 additional week at 20°C resulted in a 15.0 and 9.6% increase in pH and soluble solids content, respectively, and in a 21.5 and 4.0% decrease in acidity and ascorbic acid content, respectively (D’Aquino et al. 2001). On the other hand, storage of ‘Satsuma’ mandarins at 5°C for 21 days did not significantly affect pH, acidity, or soluble solids content of the fruit. However, when fruit was transferred from cold storage to 18°C for 7 days, a significant increase in pH and decrease in acidity and soluble solids content was observed (Hong et al. 2007). Sucrose, glucose, fructose, and citric and malic acids contents decreased during storage of ‘Hernandina’ mandarins at 5°C, but the most remarkable decrease was observed in the ascorbic acid content in fruit that was intermittently cured (18 hours at 38°C followed by 6 hours at 20°C plus 18 hours at 38°C) and subsequently stored for 9 days at 20°C (Pérez et al. 2005). In ‘Nules’ mandarins stored at ambient temperature (18–20°C), total soluble solids, acidity, sucrose, glucose, fructose, citric and malic acids, and ascorbic acid contents decreased during storage compared to initial values. Furthermore, intermittently warmed fruit (two cycles of 18 hours at 38°C) subsequently stored at ambient temperature for 1 week showed higher ascorbic acid losses (12%) compared to nonwarmed fruit (10%) (Pérez et al. 2005). Soluble solids content of ‘Sunburst’ and ‘Minneola’ mandarins increased during storage for 2 weeks at 22°C, whereas acidity decreased (Dou et al. 2004). Likewise, ‘Satsuma’ mandarins stored at 30°C showed higher soluble solids content-to-acidity ratio compared to fruit held at 18°C due to a decrease in the acidity of the fruit. Decline in total organic acids was also higher in fruit stored at 30°C (40% reduction) compared to fruit stored at 18°C (10–20% reduction), mainly due to a decrease in citric acid (Burdon et al. 2007).

Time and Temperature Effects on the Visual Quality of ‘Murcott’ Tangerines

‘Murcott’ honey tangerines shown in Figures 1.17–1.23 were harvested at the legal maturity standard for Florida, from a commercial operation in Fort Pierce, Florida, during the spring season (i.e., April). Promptly after harvest (within 6 hours), fresh tangerines were degreened according to the recommended procedures for degreening Florida citrus (Ritenour et al. 2003a; Wardowski et al. 2006). Subsequently, fruits were washed with water, but not waxed, and stored at five different temperatures (0.5 ± 0.3°C, 5.0 ± 0.2°C, 9.4 ± 0.4°C, 14.40 ± 0.4°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

‘Murcott’ tangerines stored at 0°C maintain acceptable visual quality during 76 days, showing only slight dryness at the stem-end after 50 days of storage (Figure 1.17). However, after transfer of the fruit for 2 additional days at 20°C, decay, pitting, and stem-end rind breakdown become evident (Figure 1.18). Fruit stored for 14 days at 0°C and then transferred to 20°C shows objectionable color and stem-end breakdown; pitting is noticeable in fruit after 16 days, and after 58 days decay affects the area around the stem-end of the fruit (Figure 1.18). Conversely, ‘Murcott’ tangerines stored at 5°C maintain acceptable visual quality during 76 days of storage without any apparent signs of CI or decay (Figure 1.19). However, after that time the fruits are noticeably softer than at the time of harvest.

No signs of peel pitting were observed in ‘Murcott’ tangerines stored at 10°C after 50 days of storage (Figure 1.20). After 36 days, internal evaluation shows that the peel and flesh around the stem-end are affected by decay (Figure 1.21).

‘Murcott’ tangerines stored at 15°C maintain acceptable visual quality during 32 days of storage, when slight dryness becomes noticeable at the stem-end of the fruit (Figure 1.22).

Shriveling and dryness of the peel are the major visual quality attributes that limit the postharvest life of ‘Murcott’ tangerines stored at 20°C (Figure 1.23). The fruit maintains acceptable visual quality during 24 days of storage, but after 50 days appears extremely dry and shriveled.

Overall, visual quality of ‘Murcott’ tangerines is reduced by development of pitting and decay that develop in fruit stored at 0°C and limit the postharvest life to 14 days. Storage at 5°C contributes to extended postharvest life (76 days) when compared to storage at higher temperatures. Postharvest life of tangerines stored at 10, 15, and 20°C is reduced to 18, 32, and 24 days, respectively, due to decay, shriveling, and severe fruit desiccation.

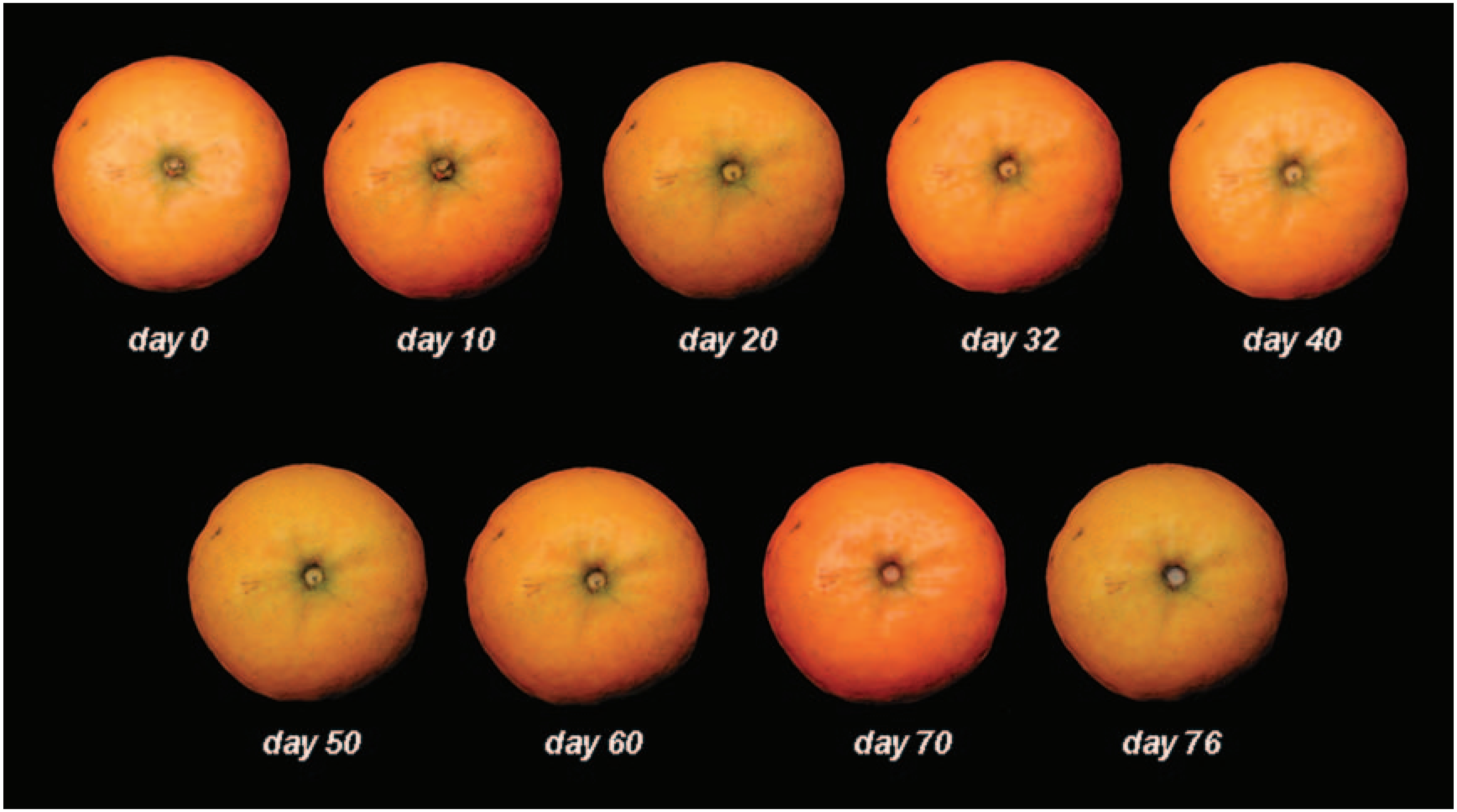
day 0
day 10
day 20
day 32
day 40
day 50
day 60
day 70
day 76

Figure 1.17. Appearance of ‘Murcott’ tangerine stored for 76 days at 0°C. Fruit maintains acceptable visual quality during 72 days of storage. Slight dryness of the stem-end develops after 50 days.

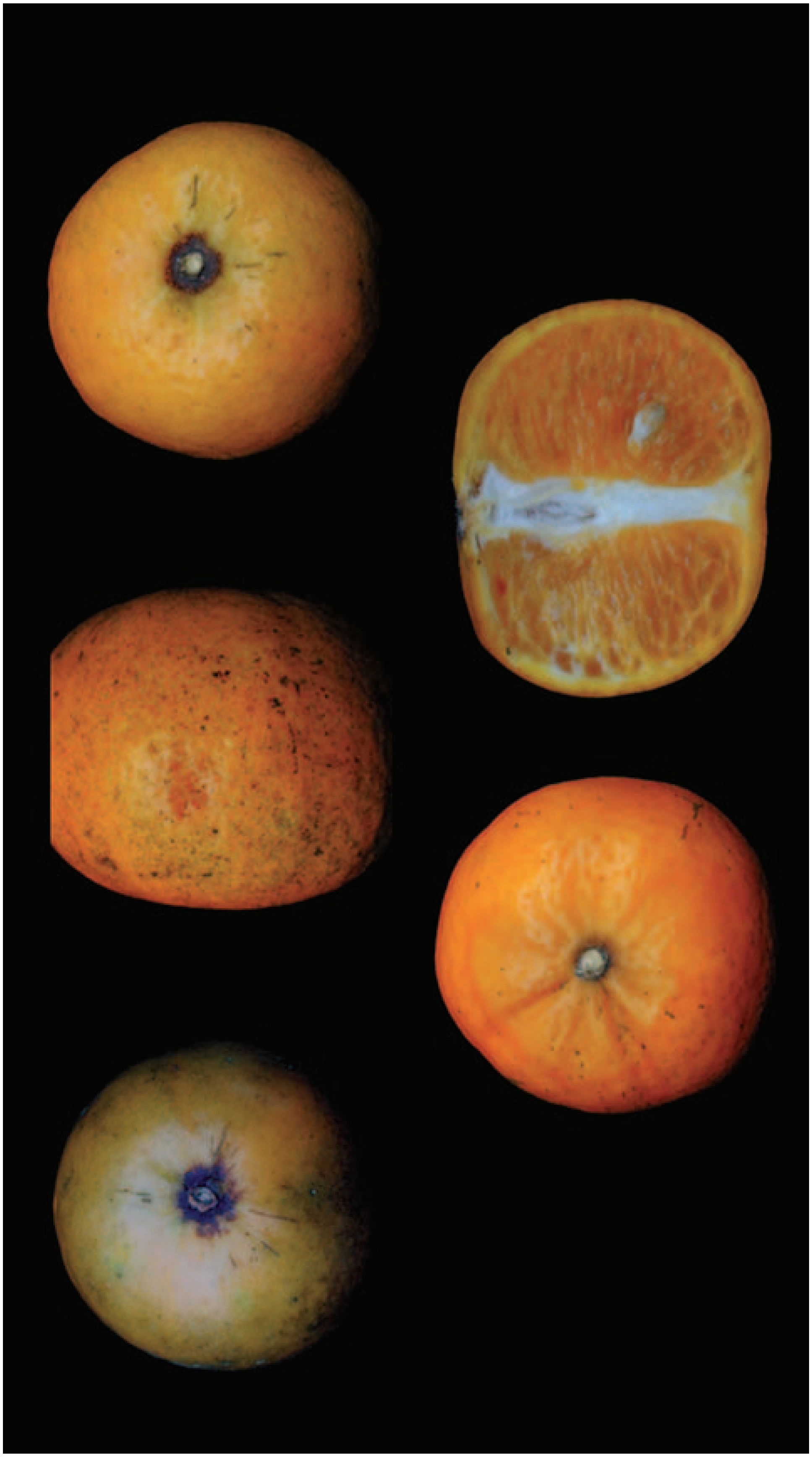

Figure 1.18. Development of decay, pitting, and stem-end rind breakdown of 'Murcott' tangerine stored for 14 (above left), 16 (above center), 18 (above right), and 58 (below) days at 0°C plus 2 additional days at 20°C.

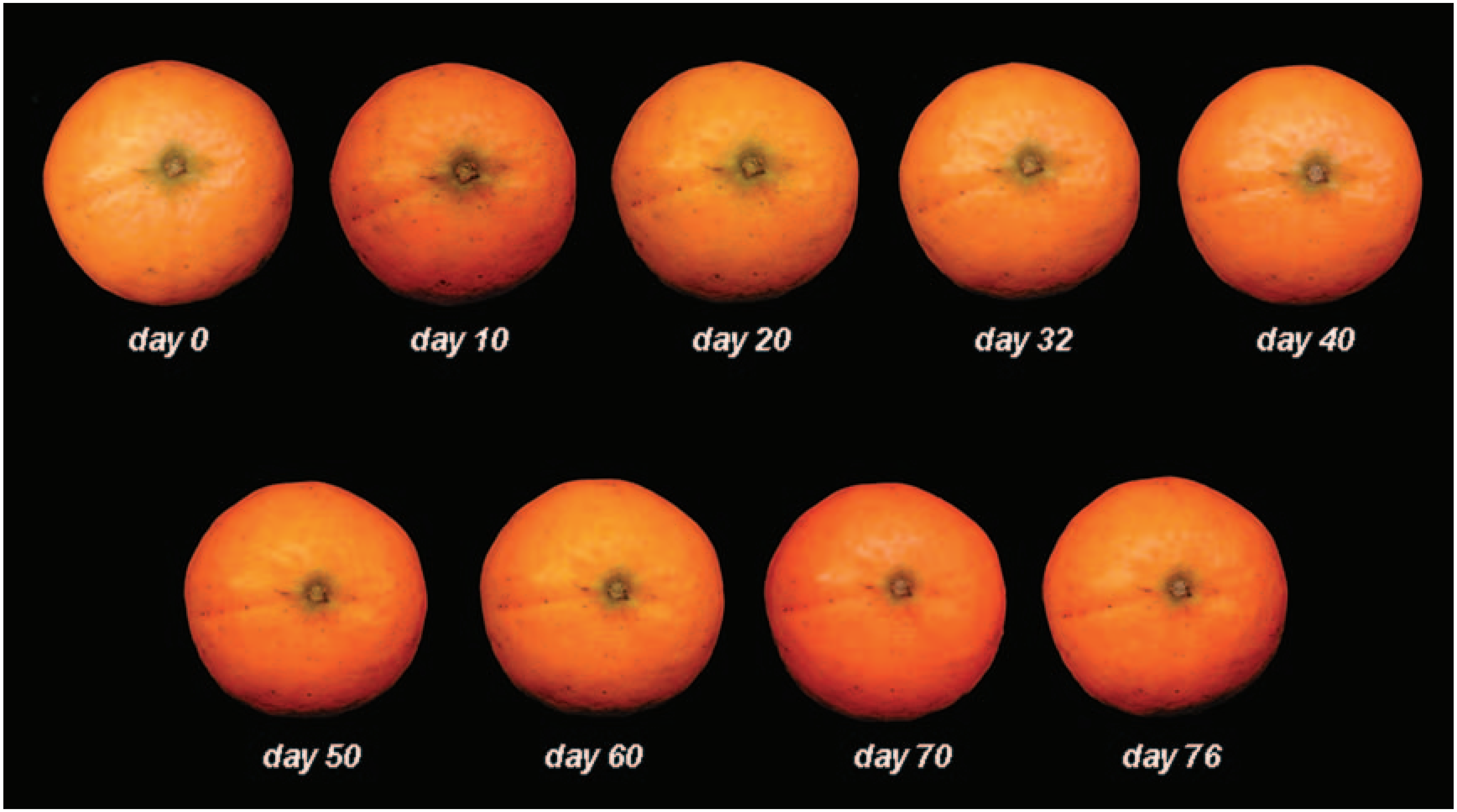
day 0
day 10
day 20
day 32
day 40
day 50
day 60
day 70
day 76

Figure 1.19. Appearance of 'Murcott' tangerine stored for 76 days at 5°C. Fruit maintains acceptable visual quality during 76 days of storage.

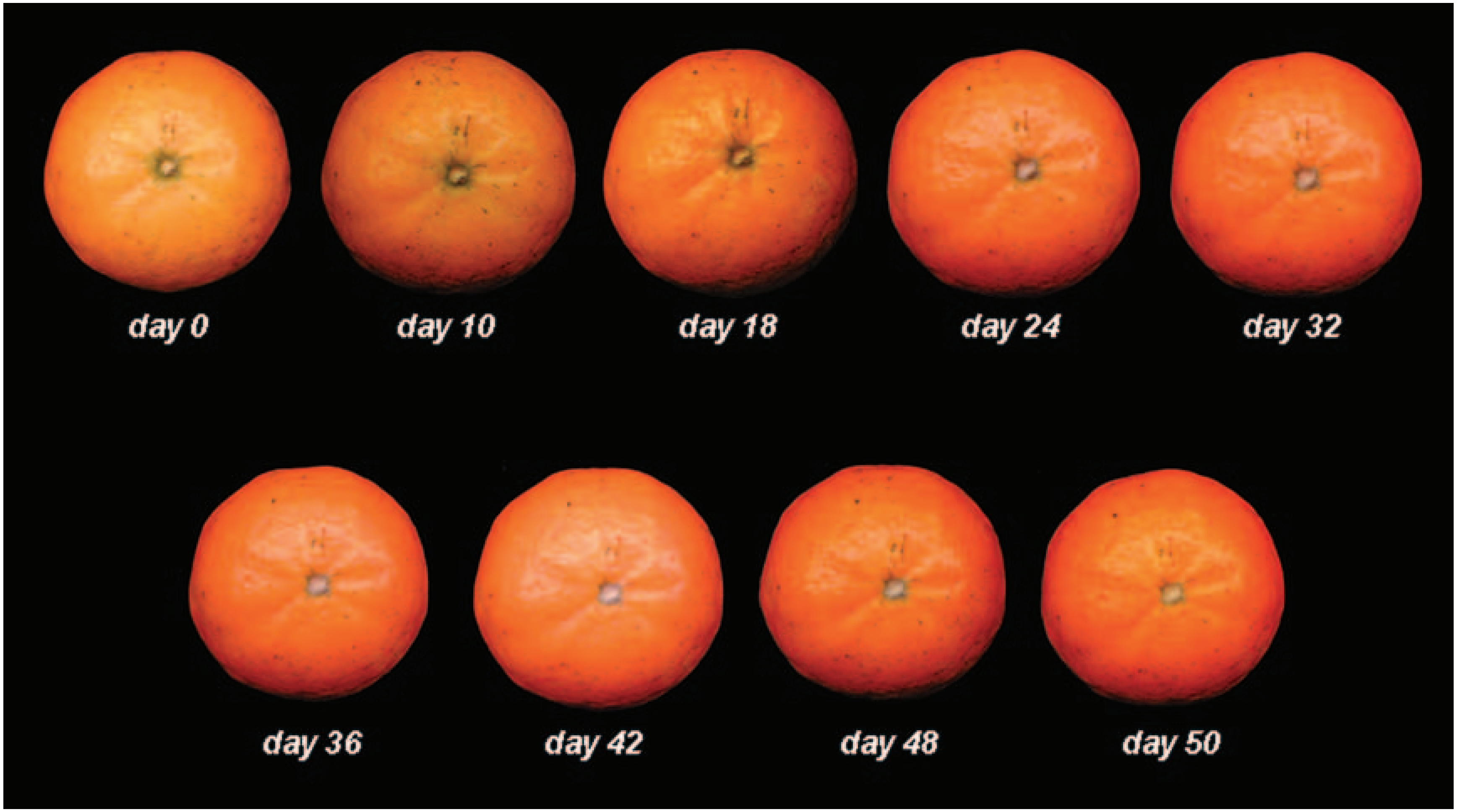
day 0
day 10
day 18
day 24
day 32
day 36
day 42
day 48
day 50

Figure 1.20. Appearance of ‘Murcott’ tangerine stored for 50 days at 10°C. Fruit maintains acceptable visual quality during 50 days of storage, but a slight mycelium growth is noticeable at the stem-end after 18 days of storage.

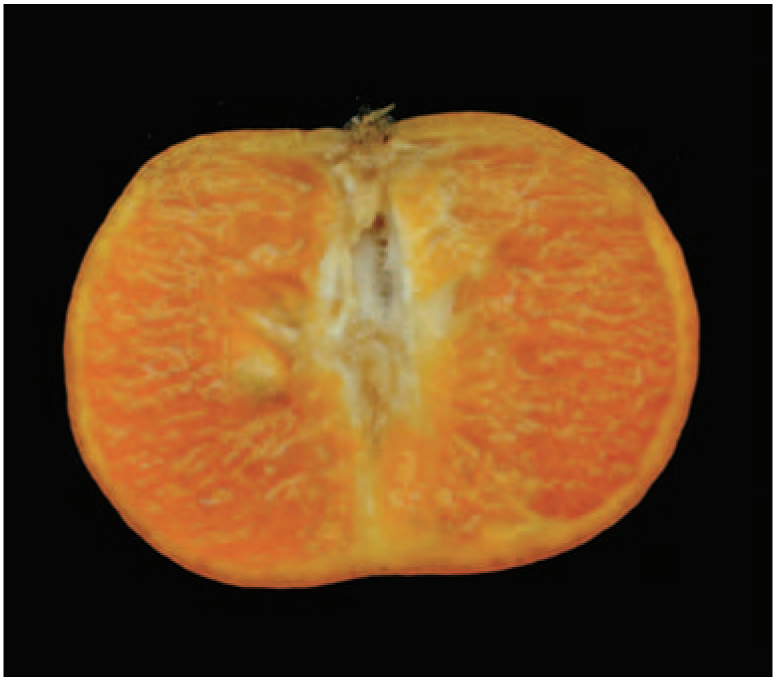

Figure 1.21. 'Murcott' tangerine peel and flesh around the stem-end affected by slight decay after storage for 36 days at 10°C.

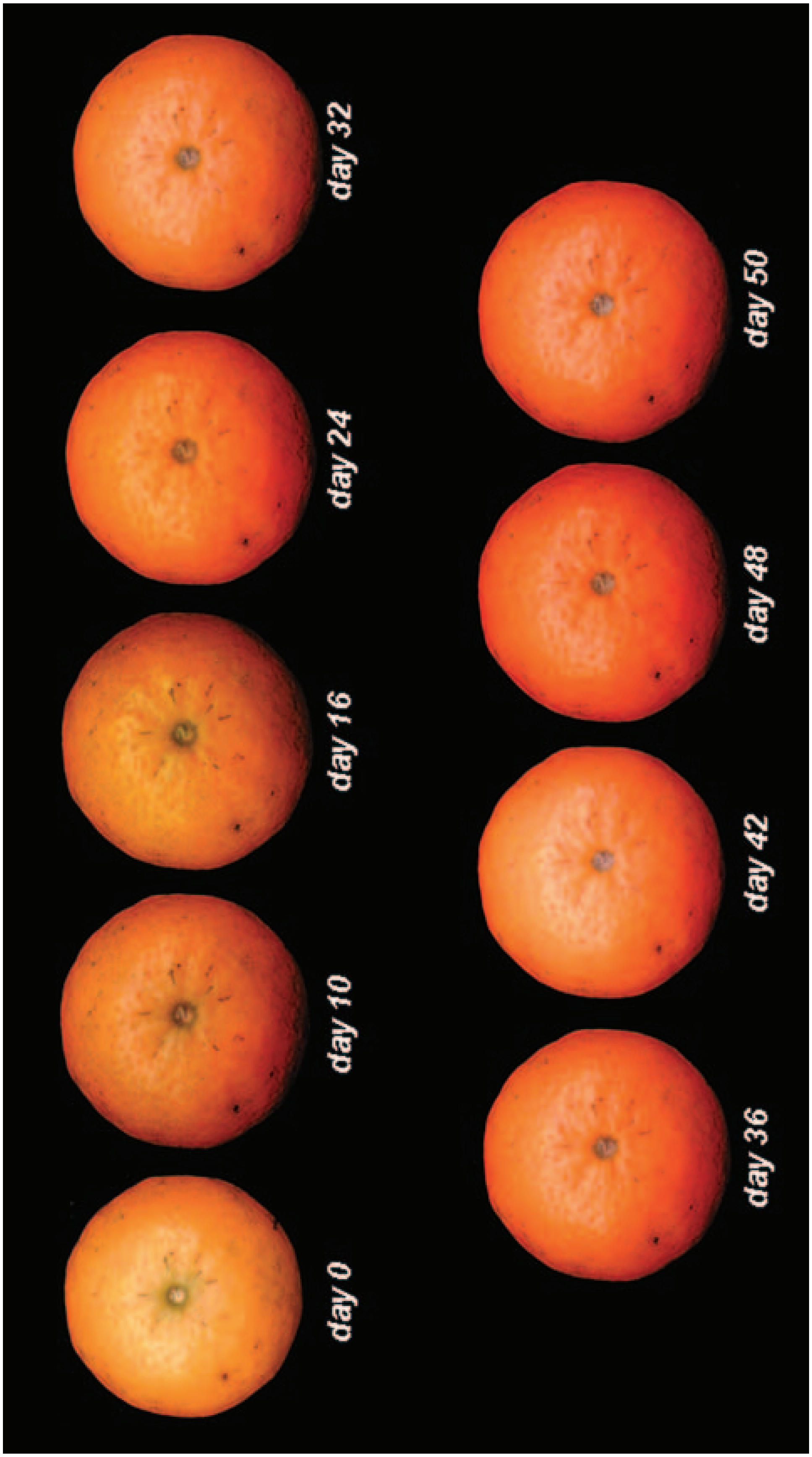
day 0
day 10
day 16
day 24
day 32
day 36
day 42
day 48
day 50

Figure 1.22. Appearance of 'Murcott' tangerine stored for 50 days at 15°C. Slight mycelium growth is noticeable at the stem-end after 32 days of storage.

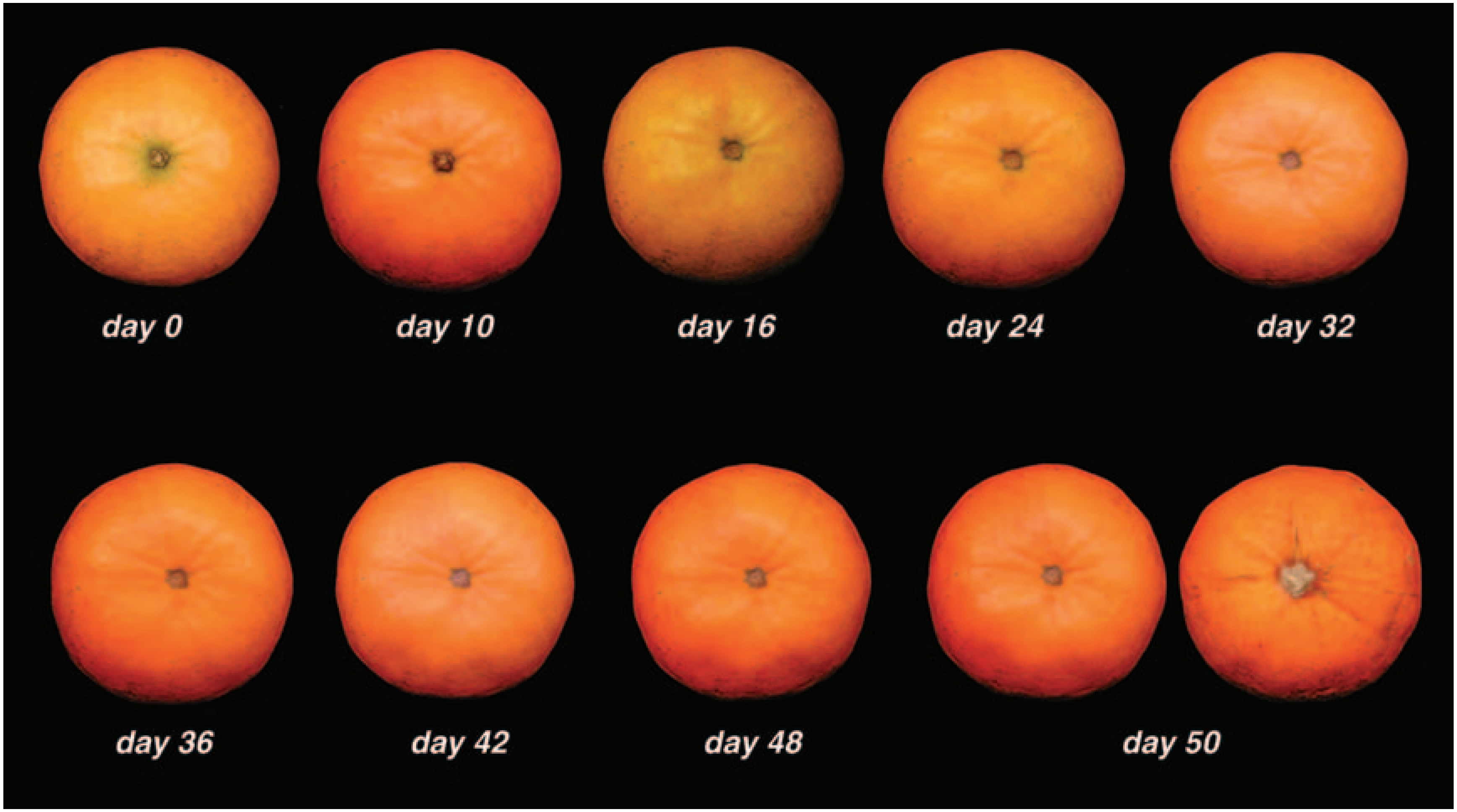
day 0
day 10
day 16
day 24
day 32
day 36
day 42
day 48
day 50

Figure 1.23. Appearance of 'Murcott' tangerine stored for 50 days at 20°C. Fruit maintains acceptable visual quality during 24 days of storage. After 50 days the fruit appears extremely dry and shriveled.

MANGO

Scientific Name: *Mangifera indica* L.
Family: Anacardiaceae

Quality Characteristics

Mango is one of the most popular fruits in the world due to its attractive color, delicious taste, and excellent nutritional properties. Mango skin color is an important component of fruit quality and, therefore, plays an important role in consumer acceptability (Medlicott et al. 1986). Usually, fruit with no green color and with more red blush is often more expensive or sells more easily (Saks et al. 1999). During ripening, most mango varieties change color from green to yellow or orange, often showing a red blush as a result of both chlorophyll loss and carotenoid synthesis (Medlicott et al. 1986). Mango flesh color changes from a greenish-yellow in green fruit, to yellow and orange in more ripe fruit. Generally fruit designated to local markets or shipments by air (i.e., a 3-day marketing frame) are harvested after the color break or medium-ripe. Fruit intended for longer transportation distances or storage (i.e., 8–10 days) is in general harvested firm and green, but physiologically mature, when the fruit "shoulders" rise above the stem-end and once there is a slight skin color change (Paull and Chen 2004). In the initial stages of mango development the L* value (lightness) measured on the skin decreases, showing afterward an increase due to the development of yellowing. An increase in a* and in b* values during ripening of mango fruit indicates a development of dark green color in the earlier stages of development, followed by the development of light yellow color when the fruit starts to ripen (Jha et al. 2006). Although mangoes harvested at the hard-green or half-ripe stage and allowed to ripen at 21°C showed similar color development, fruit developed a lighter color than fruit ripened on the tree (Lalel et al. 2003b). Such fruit are also more acid and less sweet than fruit harvested at the half or full ripe stage (Lalel et al. 2003b).

A ripe mango is soft to the touch, with a pleasant aroma, and has a flavor often described as a peach-pineapple combination (Lalel et al. 2003a). During ripening, starch is converted to sugar, which increases the fruit's sweetness. The increase in total soluble solids with increasing maturity was correlated with an increase in sucrose, fructose, and glucose and a decrease in starch (Léchaudel and Joas 2006). Although total soluble solids content increases slightly as the fruit matures, significantly greater increases were observed after the fruit reaches the mature-green stage (Jha et al. 2006). Acidity of the fruit decreases during maturation, whereas carotene, vitamin C, and aroma volatile contents increase (Lalel et al. 2003a; Tridjaja and Mahendra 2000). The decrease in mango acidity with increasing maturity was associated with a decrease in citric acid (Léchaudel and Joas 2006). Total soluble solids, sucrose, and malic-to-citric acid ratio were suggested as physiological indices for mangoes, as they provide a good description of fruit taste and maturity stage (Léchaudel and Joas 2006).

Mango fruit contains on average 82% water, 17% carbohydrates, 0.5% proteins, and 1.8% fiber (USDA 2006). When ripe, mango fruit is very rich in vitamins, especially in vitamin A due to its generous content of β-carotene that may range from 350 to 6,700 μg (Hulme 1971; Mendoza and Wills 1984). Depending on the cultivar, stage of maturity, and environmental factors during development in the field, as well as handling conditions during postharvest, mango fruit may contain 3,894 IU of vitamin A and 28 mg of vitamin C per 100 g of fresh fruit (USDA 2006).

Optimum Postharvest Handling Conditions

Optimum postharvest conditions for mango storage depend on fruit maturity at harvest, storage duration, and temperature, and also the time of harvest within the season (Medlicott et al. 1990). Mango fruit is very sensitive to cold temperatures, and prolonged storage periods at temperatures below 10°C may delay ripening of the fruit and lead to CI. Depending on the cultivar, maturity stage, and season of harvest, some mango fruit can be stored between 7 and 8°C for 25 days, whereas others require temperatures above 13°C. Green fruit should be stored between 10 and 15°C, whereas ripe fruit can tolerate much lower temperatures. Therefore, to reduce the risk of CI, recommended storage temperatures for mangoes are between 12 and 13°C (Medlicott et al. 1990; Mitra and Baldwin 1997). For long-term storage (i.e., more than 21 days) mature and half-mature mangoes should be stored at 12°C, whereas storage of immature fruit at 8°C should be avoided (Medlicott et al. 1990).

Temperatures in the range of 18–22°C have been reported to be the best for development of typical aroma, flavor, and other quality attributes of 'Tommy Atkins' (Medlicott et al. 1986), 'Haden,' 'Irvin,' 'Keitt,' 'Kent' (Vazquez-Salinas and Lakshminarayana 1985), 'Kensington' (O'Hare 1995), and 'Kensington Pride' mango fruit (Lalel et al. 2003b).

In addition to an optimum temperature, a relative humidity between 85 and 90% should be maintained throughout the postharvest handling to reduce the occurrence of wilting and shriveling (Paull and Chen 2004).

Temperature Effects on Quality

Appearance of mango fruit is impaired by the development of shriveling due to moisture loss, softening, discoloration, or accelerated ripening due to exposure to ambient warm temperatures, and by CI symptoms due to exposure to chilling temperatures.

When mango is stored at temperatures below 10°C, CI symptoms may develop on the fruit. However, the symptoms may vary with maturity of fruit at harvest, cultivar, temperature at which symptoms became evident, and length of exposure to that temperature. Symptoms of CI are generally characterized by a grayish, scald-like discoloration or skin browning, followed by pitting, uneven ripening, suppressed pulp color, poor flavor due to decreased production of aroma volatile, reduced ability to metabolize acids, and increased susceptibility to decay (Mitra and Baldwin 1997). Skin injuries (i.e., discoloration or uneven coloration, pitting, grayish scald) are usually the first symptoms of CI to develop, and the intensity of the injury often increases after holding the fruit at ambient temperatures (Nunes et al. 2007; Phakawatmongkol et al. 2004). Internal injury, such as pulp discoloration, usually occurs later than skin discoloration. For example, mangoes exposed to temperatures between 4 and 8°C developed grayish scald-like spots on the skin, followed by the development of large dark brown areas on the skin. Severe skin discoloration was accompanied by uneven pulp softening and poor eating quality due to reduced volatile production (Phakawatmongkol et al. 2004). Aroma volatile production decreased as CI index increased and was significantly lower in mangoes stored at 0, 5, or 10°C, compared to storage at 20°C (Nair et al. 2003). The reduction in aroma volatile production due to CI has been attributed to the suppression of various enzymes involved in the conversion of acetyl coenzyme A to volatile compounds (Nair et al. 2003), the suppression of biosynthesis of fatty acids, which are precursors of the biosynthesis of aroma volatiles (Lalel et al. 2003b), and also the suppression of ethylene biosynthesis caused by CI (Nair et al. 2004b). In fact, ethylene production was significantly decreased during ripening in mango fruit stored at 0, 5, and 10°C (Nair et al. 2004b).

'Kensington' mature-green mangoes developed severe symptoms of CI after 3 weeks at 1°C (Chaplin et al. 1991). Ketsa et al. (2000) reported that mangoes stored at 4°C for 3 weeks developed moderate CI, such as blackened lenticels and grayish patches on the peel, after transfer to ambient temperatures. When 'Kensington Pride' mangoes were stored at 5°C for 2 weeks, CI symptoms such as darkening of the skin, prominence of lenticels, poor color and flavor, and uneven ripening developed on the fruit upon transfer to 22°C (Nair et al. 2004a). Skin browning in 'Kensington' mangoes was evident after 1 week at 5°C, whereas reduced pulp color and increased acidity occurred at temperatures higher than 7°C (O'Hare and Prasad 1993). Although decay may remain low in mango fruit continuously stored at 2 or 5°C, pitting that develops on the skin of the fruit upon transfer to 20°C may be readily attacked by pathogens, resulting in rapid decay and complete loss of the fruit (Nunes et al. 2007). Ketsa et al. (2000) reported that when Thai mangoes were exposed to 4°C for 3 weeks decay rapidly increased upon removal of the fruit from cold storage. Immature-green mango stored at 10°C for 7 days developed CI. After 21 days the symptoms worsened. The pitted areas became dark-brown, originating from the stem-end and then spreading to the shoulders of the fruit. The peel of such fruit had a dry and dull appearance with large pockets of white mycelia (Wickham and Mohammed 1999). Although 'Tommy Atkins,' 'Keitt,' and 'Amelie' immature, half-mature, and mature mangoes stored at 8 or 10°C retained firmness during storage, ripening was inhibited, and fruit did not develop normal peel and pulp coloration upon transfer to ambient temperatures (Medlicott et al. 1990). CI index in mature-green 'Kensington Pride' mangoes increased compared to nonchilled fruit as the storage temperature decreased from 10 to 0°C or the storage period increased from 1 to 28 days (Nair et al. 2003).

Pre-storage heat treatments may alleviate CI symptoms during cold storage and reduce levels of decay in mango fruit. For example, mango preheated for 3 days at 38°C and subsequently stored at 4°C for 3 weeks showed normal ripening, as evidenced by decreasing firmness and acidity and increasing soluble solids content. In addition, preheated fruit showed lower levels of decay and CI compared to nonheated fruit after storage at 4°C (Ketsa et al. 2000). Likewise, heating 'Keitt' mango fruit to 38°C for 24–48 hours before storage at 5°C for 11 days significantly reduced CI symptoms (i.e., rind pitting and discoloration) and increased color development and soluble solids content compared to nonheated fruit (McCollum et al. 1993). There was no significant difference in fruit firmness.

In mango fruit stored at nonchilling temperatures, loss of moisture, softening, color changes, and decay are in general the major causes for quality loss. Jacobi et al. (1995b) reported that skin color development in mangoes depends on the cultivar and maturity. In addition, the rate of ripening depends upon the storage conditions, particularly the temperature. During storage, L*, hue, and chroma values measured on the skin of 'Tommy Atkins' and 'Palmer' mangoes changed rapidly to approach a value that indicated that the fruits were fully reddish-yellow after 7–8 days at 20°C. L* value of 'Tommy Atkins' mangoes stored at 20°C increased during storage, indicating that the fruits were more light than at the time of harvest due to the development of a yellowish color (Nunes et al. 2007). Jacobi et al. (1995b) reported that the L* value of 'Kensington' mangoes increased after 12 days in storage at 22°C. In mangoes stored at 35°C, L* value increased significantly after 10 days of storage and then decreased slightly due to the appearance of black spots (Jha et al. 2006). Hue tended to decrease during storage, indicating a shift in the color of the fruits from a greenish-yellow to orange-yellow, particularly in 'Tommy Atkins' mangoes stored at 20°C (Nunes et al. 2007). Decrease in the hue value has also been reported for 'Kensington' mangoes stored for 10–12 days at 22°C (Jacobi et al. 1995b). Similarly, decrease in the hue angle of 'Tommy Atkins' and 'Kensington Pride' mangoes was observed as the temperature increased from 13 to 20°C (Saks et al. 1999). Chroma of mangoes tended to increase during storage, particularly in fruits stored at temperatures higher than 5°C. For example, chroma of 'Kensington' mangoes stored for 12 days at 22°C increased compared to the time of harvest (Jacobi et al. 1995b). Increase in chroma value indicates a shift from a dull to a more vivid reddish-yellow color of the mango skin (Nunes et al. 2007). When stored for 21 days at 12°C, immature, half-mature, and mature mango cultivars completed their ripening process, as shown by peel color development; however, the rate of changes was faster in mature compared to less mature fruit (Medlicott et al. 1990). Green mature mangoes stored at 13°C were almost ripe or overripe after 24 and 38 days of storage, respectively (Lalel et al. 2005). However, after 8–5 days, 'Tommy Atkins' and 'Palmer' mangoes, respectively, may develop objectionable softness (Nunes et al. 2007). Likewise, mango fruit from Haiti (cv. Francisque) stored at 12°C ripened completely and developed a good flavor after the first week of storage (Kane et al. 1982). Mature-green 'Kensington' mangoes stored at 15°C showed a significant decrease in firmness, especially at between 1 and 2 weeks of storage, and after 3 weeks the fruit was considered fully ripe (Chaplin et al. 1991). Less mature fruit, that is, mature-green 'Kensington' mangoes, held continuously at 20°C were also fully ripe after 1 week of storage (Chaplin et al. 1991). Likewise, Medlicott et al. (1986) reported that after 9 days 'Tommy Atkins' mango fruit harvested at the fully mature-green stage ripened at 22°C and developed good quality characteristics, such as extensive chlorophyll breakdown in the skin. Skin yellowness of 'Kensington' mangoes increased, becoming evident after 2–6 days at 22°C (Jacobi et al. 1998).

Talcott et al. (2005) reported that 'Tommy Atkins' mangoes harvested at the mature-green stage began to show characteristic signs of ripening, such as external skin coloration and softening, after storage for 8 days at 20°C. Other authors also reported a decrease in the firmness of 'Tommy Atkins' mangoes stored at 20°C (Jacobi et al. 1998; Mahayothee et al. 2002; Saks et al. 1999). For example, Jacobi et al. (1998) reported that unripe 'Kensington' mangoes showed the first signs of softening after 4 days in storage at 22°C; after 8 days fruits were considered to have advanced softening, and after 11 days they were considered fully soft or ripe. Mahayothee et al. (2002) reported that firmness of Thai cultivars of mangoes harvested at the mature-green stage decreased during the first 3 or 4 days of ripening at 23°C, whereas firmness of fruit stored at 35°C decreased continuously until 7 days of storage, beyond which the rate of softening was significantly high (Jha et al. 2006). On the other hand, mangoes stored for 2 weeks at 0, 2, or 5°C were still firm, whereas fruit stored at 14 or 20°C started to soften. However, when transferred to 20°C after 2 weeks at chilling temperatures, fruits started to soften after 9 days, but the quality was objectionable mostly due to chilling damage (Lederman et al. 1997).

Postharvest heat treatments (i.e., hot air, vapor, or water) are often used to control pests and diseases of mango fruit. However, exposure of the fruit to temperatures that are too high and for extended periods may cause detrimental effects on mango visual and eating quality. For example, visible symptoms of skin injury caused by immersion of mango fruit in a 47°C water bath for 25 minutes included translucence, shriveling, dimples, brown discoloration, and decay, whereas visible symptoms of pulp injury were starchy bands of variable thickness, small starch islands near the stem, and air-filled voids at the stem and near the seed (Jacobi et al. 2001b; Joyce and Shorter 1994; Ponce de Léon et al. 1997). Exposure of 'Haden' mangoes to hot water at 46.1°C for 90 minutes hastened cuticle expansion causing initial isolated fissures and enlarged pores (Ponce de Léon et al. 1997) that may later contribute to accelerated moisture loss during storage. Jacobi et al. (1995a, 1995b, 1996, 2000, 2001a, 2001b, 2002) have done extensive work on the effects of several heat treatments on the quality of 'Kensington' mango fruit. For example, exposure of 'Kensington' mangoes to a 46°C hot-water treatment for 30 minutes followed by storage at 22°C for 7 days resulted in increased fruit softening and in 73% of fruit showing scalding, which aggravated with increased exposure times (Jacobi et al. 1995a). However, exposure of immature and mature mango fruit to high-humidity hot-air treatment to a fruit core temperature of 46.5°C for 10 minutes resulted in a better retention of fruit firmness and skin color, and there were no external or internal heat injuries observed in any of the maturity stages. Furthermore, heat-treated fruits maintained characteristic sensorial qualities of mangoes (Jacobi et al. 1995b). Nonetheless, adding a disease control treatment of water dipping at 55°C for 5 minutes to the previous hot-water treatment of 46.5°C for 10 minutes resulted in severe fruit injury in the form of skin browning and lenticel spotting and increased softening compared to nonheated fruit (Jacobi et al. 1996). Likewise, vapor heat treatment for 15 minutes at 47°C resulted in softer fruit and increased color rating associated with accelerated ripening, but no disease was recorded in heat-treated compared to nontreated mango (Jacobi and Giles 1997). Hot-water treatment at 47°C for 15 minutes increased weight loss by 50% and fruit softness by 15%, and reduced skin yellowness by 40–51% compared with non-heat-treated fruit. However, conditioning the fruit at 22 or 40°C for 16 hours prior to the heating treatment resulted in less weight loss, prevented the appearance of cavities, and reduced hot-water injuries (Jacobi et al. 2000, 2001a). Furthermore, conditioning mango fruit at 40°C for 16 hours resulted in a fruit with 11–37% higher soluble solids content and lower acidity levels compared to nonconditioned fruit (Jacobi et al. 2001a). Starch degradation was accelerated by conditioning mango fruit at 40°C for 8 hours previous to heat treatment at either 45°C for 30 minutes or 47°C for 15 minutes, and, consequently, soluble solids content was higher in conditioned fruit compared to nonconditioned fruit (Jacobi et al. 2002).

Loss of moisture increased during storage of 'Tommy Atkins' and 'Palmer' mangoes, regardless of storage temperature, but there was no significant difference in the weight loss of mango fruit stored at 2°C compared to that of fruit stored at 5°C (Nunes et al. 2007). Although storage of mangoes at temperatures between 20 and 22°C with 85–95% relative humidity has been recommended for ripening of mangoes (Paull and Chen 2004; Vazquez-Salinas and Lakshminarayana 1985), weight loss in fruit stored at 20°C was greater when compared to that of fruit stored at lower temperatures (Nunes et al. 2007). Reddy and Raju (1988) reported an average 3.96% weight loss in 'Alphonso' mangoes stored at ambient temperature for 5 days compared to 3.9 and 3.7% weight loss in 'Tommy Atkins' and 'Palmer' mangoes stored at 20°C for 5 days. For example, the weight loss value obtained for 'Tommy Atkins' mangoes stored for 18 days at 12°C (7.8%) corresponded to a shriveling level below the maximum acceptable before the visual quality of the fruit became objectionable. However, the maximum weight loss obtained for 'Palmer' mangoes (6.5% after 14 days at 12°C) corresponded to a shriveling level close to the maximum acceptable before the fruit became unacceptable for sale. Shriveling of mangoes is not considered an important quality factor if the relative humidity is maintained above 85% (Nunes et al. 2007).

Chemical composition of mangoes changes during storage, and in general, soluble solids and total sugar contents of 'Tommy Atkins' mangoes tended to increase when the fruit was stored at temperatures higher than 12°C (Medlicott et al. 1986). In mangoes stored at 12°C total sugar increases during 16 days of storage, whereas in mangoes stored at 32°C, the sugar content reaches a maximum after 6 days. Conversely, acidity of the fruit tends to decrease during storage. Acidity of 'Tommy Atkins' mangoes stored at 12 and 17°C was reduced by 26 and 58%, respectively, compared to an 86% reduction in fruit stored at 22°C (Medlicott et al. 1986; Vazquez-Salinas and Lakshminarayana 1985). Upon transfer to ambient temperature, immature mangoes stored for 21 days at 12°C showed a slight increase in soluble solids content and decrease in acidity, whereas half-mature and mature fruits showed a highly significant increase in soluble solids content and acidity loss (Medlicott et al. 1990). Storage at lower temperatures (i.e., between 6 and 8°C), however, tends to delay the decrease in acidity and the increase in soluble solids content of 'Tommy Atkins' mangoes, independent of the ripening stage of the fruit (Morais and Assis 2004). In 'Kensington' mangoes stored at 1°C the total soluble solids content showed a significant decrease between the third and fourth weeks of storage (Chaplin et al. 1991). Fruits with severe CI did not reach the normal soluble solids and citric acid levels after 4 weeks at 0 or 2°C, which were attained by fruits stored at 14 and 20°C (Lederman et al. 1997).

Depending on the mango cultivar, ascorbic acid losses between 16 and 23% may occur during storage at temperatures between 16 and 28°C, respectively (Vazquez-Salinas and Lakshminarayana 1985). That is, the higher the storage temperature the higher the losses in ascorbic acid. However, fruit held at temperatures greater than 17°C develops higher carotenoid content compared to fruit held at 12°C (Medlicott et al. 1986; Talcott et al. 2005; Vazquez-Salinas and Lakshminarayana 1985). Conversely, mangoes stored at 13°C had a lower carotenoid content and higher chlorophyll content even after 20 days, compared to fruit ripened at 22°C. Likewise, carotenoid synthesis was delayed when mango fruit was stored at 10°C compared to storage at ambient temperature. Although at ambient temperature, β-carotene increased rapidly within 14–15 days, at 10°C it increased slowly until 45 days of storage (Kapse et al. 1988). As observed at low temperatures, storage of mango fruit at 30°C also resulted in poor carotenoid development and higher chlorophyll retention in the skin. Such fruit also had less flavor compared to fruit ripened at 18 or 22°C (O'Hare 1995).

Time and Temperature Effects on the Visual Quality of 'Palmer' and 'Tommy Atkins' Mangoes

'Palmer' and 'Tommy Atkins' mangoes shown in Figures 1.24–1.41 were harvested medium-ripe (more than 50% yellow or red) from a commercial operation in Floral City, Florida, during the summer season (i.e., July). Promptly after harvest, fresh mango was stored at five different temperatures (2.0 ± 0.3°C, 5.0 ± 0.2°C, 12.0 ± 0.4°C, 14.40 ± 0.4°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Skin injuries and decay are the major visual quality changes in half-ripe 'Palmer' and 'Tommy Atkins' mango cultivars stored at temperatures lower that 12°C, whereas accelerated ripening and decay contribute to the major visual quality changes in fruit stored at temperatures higher than 12°C.

'Palmer' mangoes stored at 2°C develop severe symptoms of CI such as skin pitting, scalding, uneven ripening, and increased decay, which worsen when the fruit is transferred to ambient temperature. After approximately 9 days 'Palmer' mangoes stored continuously at 2°C show slight skin pitting or scalding (Figure 1.24). However, the symptoms appear much more severe upon transfer of the fruits to 20°C for 2 additional days (Figure 1.25). Initial symptoms of CI in 'Palmer' mangoes, such as slight pitting and skin discoloration, develop after 3 days at 2°C upon transfer to 20°C for 2 additional days. With increased chilling exposure time, the fruit develops objectionable appearance due to the development of pitting, scalding, uneven ripening, grayish discoloration of the skin, and bruised-like brownish areas of decay (Figure 1.25 and 1.26). Furthermore, after transfer to ambient temperature the fruit softens rapidly.

'Palmer' mangoes stored at 5°C also develop CI symptoms, but later and to a lesser extent than fruit stored at 2°C. After 15 days of continuous storage at 5°C, mango fruits show minor signs of CI such as small pits and skin discoloration (Figure 1.27). However, the symptoms worsen and develop to a moderate to severe level when the fruit is transferred to 20°C for 2 additional days (Figure 1.28). Initial symptoms of CI developed upon transfer to 20°C in fruits stored for 6 days at 5°C, and aggravate with increasing storage time. In addition to developing a scald-like appearance, grayish discoloration, uneven ripening, pitting, and decay of the pits, mango fruit becomes very soft.

Visual quality of 'Palmer' mangoes stored at 12°C is reduced to 12 days due to the development of decay (Figure 1.29). On day 14 the fruit appears overripe, whereas black spots of decay affect the surface of the fruit. Slight shriveling (i.e., vertical wrinkles) is also noticeable in some parts of the fruit, particularly near the stem-end and at the bottom part where the fruit body narrows.

Decay develops very quickly in 'Palmer' mango fruit stored at 15°C (Figure 1.30). After 3–5 days black spots at the stem-end of the fruit become evident and increase in size and number as storage progresses. Brown areas of necrotic tissue appear first at the stem-end of the fruit and then spread to the shoulders and then to the body of the fruit. After 7 days, other dark necrotic spots develop on the fruit surface, and on day 10 the fruit is covered with large black spots of decayed areas.

Color of 'Palmer' mangoes develops very quickly when fruit is stored at 20°C. The color of the fruit changes from a greenish-yellowish-red at the time of harvest to a reddish-yellow after 8 days of storage (Figure 1.31). 'Palmer' mangoes maintain acceptable visual quality during 4–5 days and are completely ripe after 6 days. Yet an area of decayed tissue develops at the equatorial part of the fruit and reduces the visual quality of the fruit. Softening becomes objectionable after 6 days when fruit appears fully ripe. After 8 days, decay and shriveling (i.e., vertical wrinkles) develop in some mangoes and depreciate fruit visual quality (Figure 1.32).

'Tommy Atkins' mangoes develop symptoms of CI similar to those observed in 'Palmer' mangoes. After 9 days, minor pitting of the skin develops in fruit stored continuously at 2°C (Figure 1.33). However, upon transfer of the fruit to 20°C for 2 additional days symptoms aggravate. Pitting of the skin, flesh damage near the peel, and discoloration develop in fruit after 3 days at 5°C upon transfer to 20°C (Figure 1.34). The symptoms aggravate with increased storage; after 12 days the fruit visual external quality becomes objectionable due to pitting, uneven ripening, and scalding, whereas the flesh appears soft, spongy, and discolored. After 15 days the visual quality of the fruit is completely deteriorated due to scalding, pitting, and uneven ripening.

When stored at 5°C, 'Tommy Atkins' mangoes maintain acceptable quality during 12 days, and after 15 days fruit shows very subtle signs of CI, such as small pits and discoloration (Figure 1.35). After transfer of the fruit to 20°C for 2 additional days, CI symptoms aggravate. After 3 days the skin of the fruit develops areas of grayish discoloration, scalding, pitting, and uneven ripening (Figure 1.36). After 6 days, the flesh adjacent to the skin deteriorates due to tissue damage. The flesh of the mango fruit is discolored, soft, and spongy after 15 days.

Changes in color from green to reddish-yellow throughout storage are evident in 'Tommy Atkins' mangoes held at 12°C. Mangoes maintain acceptable visual quality during 12 days; after 18 days the fruit appears completely ripe, yet decay becomes objectionable due to development of several areas of black necrotic tissue spread all over the fruit surface (Figures 1.37 and 1.38). At this time the fruit is extremely soft and cedes easily to finger pressure.

Decay develops rapidly in 'Tommy Atkins' mangoes stored at 15°C, and the small skin defects near the stem-end of the fruit, which appear initially (day 0), become large areas of decayed tissue in both sides of the fruit after 9 days of storage (Figures 1.39 and 1.40). Decay originates initially at the stem-end of the fruit and then spreads to the shoulders and all the way down to the body of the fruit. Fruit color also changes during storage, and after 7 days the fruit is completely ripe, yet visual quality is impaired by decay. Therefore, 'Tommy Atkins' mango fruit stored at 15°C maintains acceptable visual quality only during 2–3 days.

Development of decay and changes in color from green to fully yellow occur rapidly in 'Tommy Atkins' mangoes stored at 20°C (Figure 1.41). The fruit maintains acceptable visual quality during 2–3 days at this temperature, but after 7 days the fruit is completely yellow and one of the sides covered with black spots of decayed tissue. It is interesting to see that initial small defects on the skin of the fruit may become large necrotic areas after only a few days of storage at 15 or 20°C (Figures 1.39 and 1.41).

Overall, 'Palmer' and 'Tommy Atkins' mangoes stored at 12°C maintain better visual quality for longer periods (12 days) when compared to storage at a lower or higher temperature. Postharvest life of 'Palmer' mangoes stored at 2 and 5°C is reduced to 3 and 6 days, respectively, due to CI, whereas quality of the fruit stored at 15 and 20°C deteriorates after 5 days due to decay, shriveling, and overripe appearance. 'Tommy Atkins' postharvest life is reduced to 3 days at 5, 15, or 20°C.

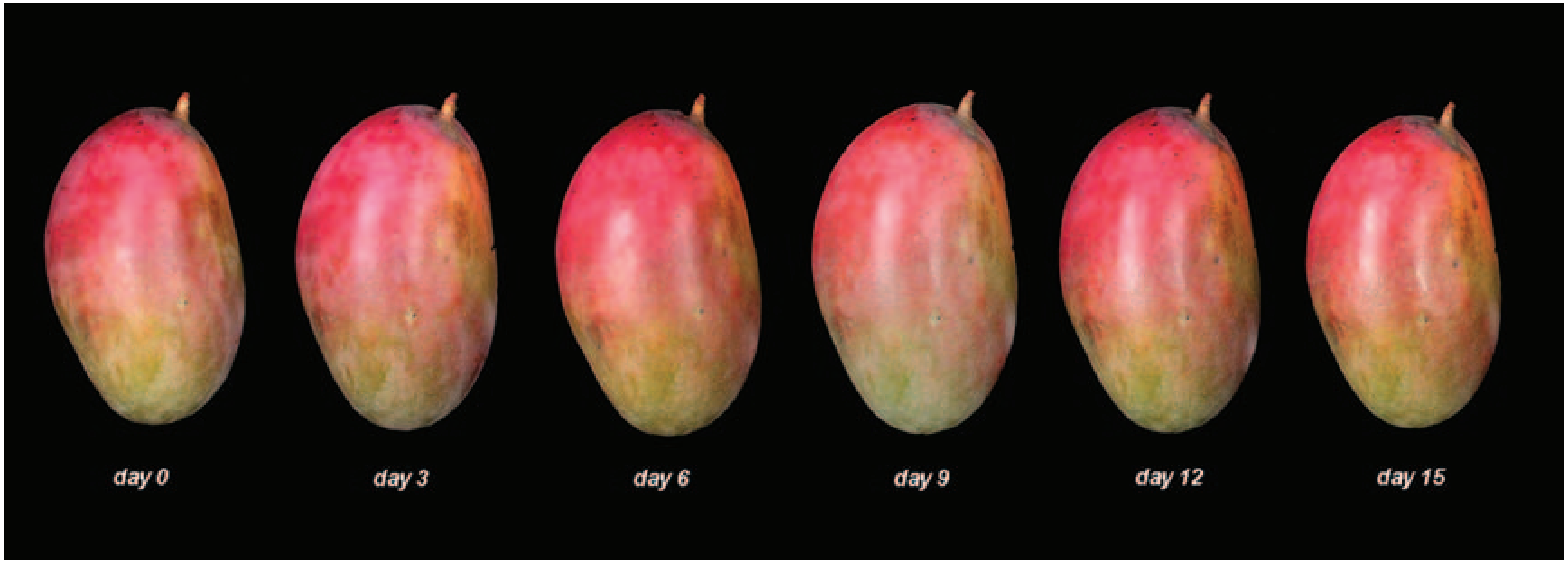
day 0
day 3
day 6
day 9
day 12
day 15

Figure 1.24. Appearance of 'Palmer' mango stored for 15 days at 2°C. After 9 days slight pitting of the skin becomes apparent.

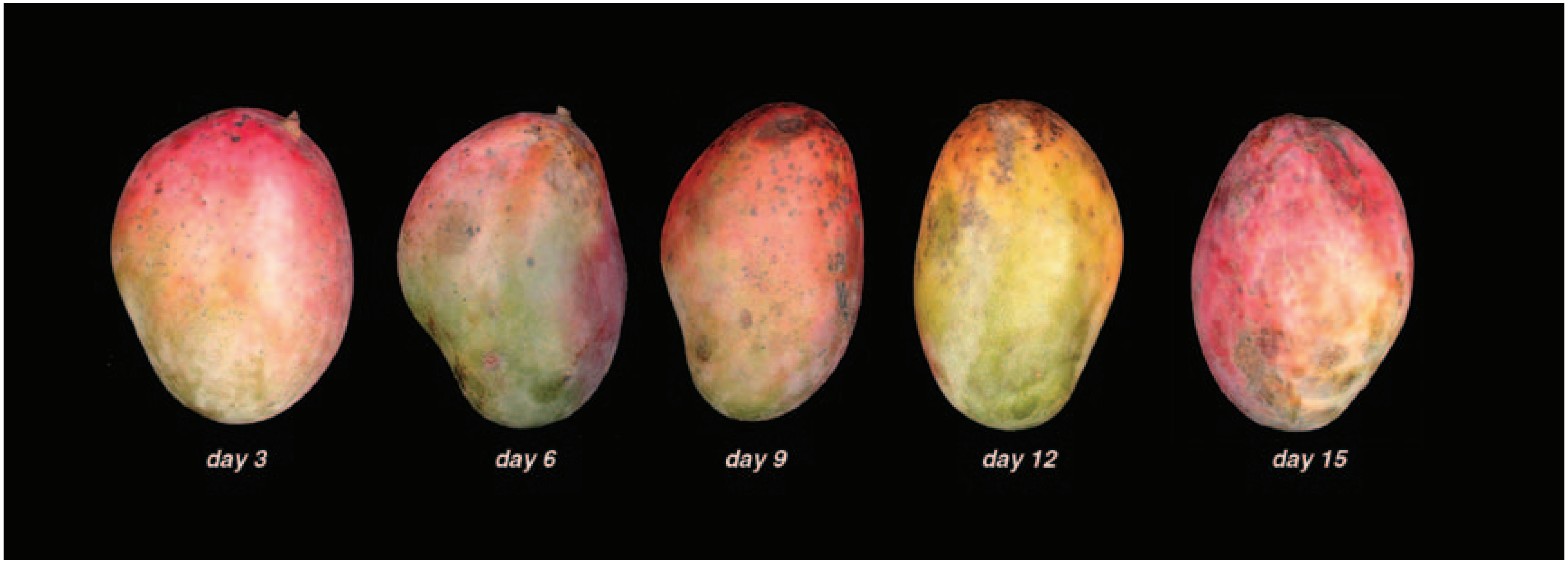
day 3
day 6
day 9
day 12
day 15

Figure 1.25. Chilling injury in 'Palmer' mango after storage at 2°C plus transfer for 2 days at 20°C. Fruit shows uneven ripening, discoloration, pitting, and scalding.

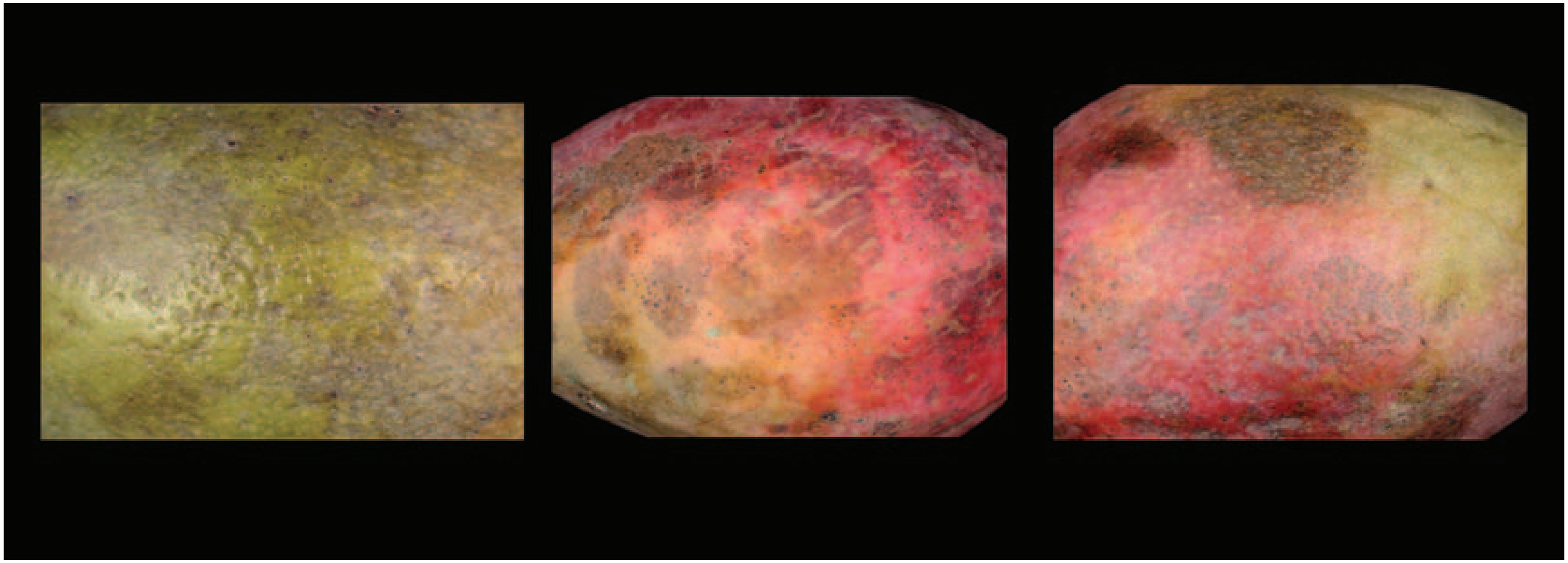

Figure 1.26. Pitting, scalding, and decay in 'Palmer' mango after storage for 12 days (left) and 15 days (center and right) at 2°C plus transfer for 2 days at 20°C.

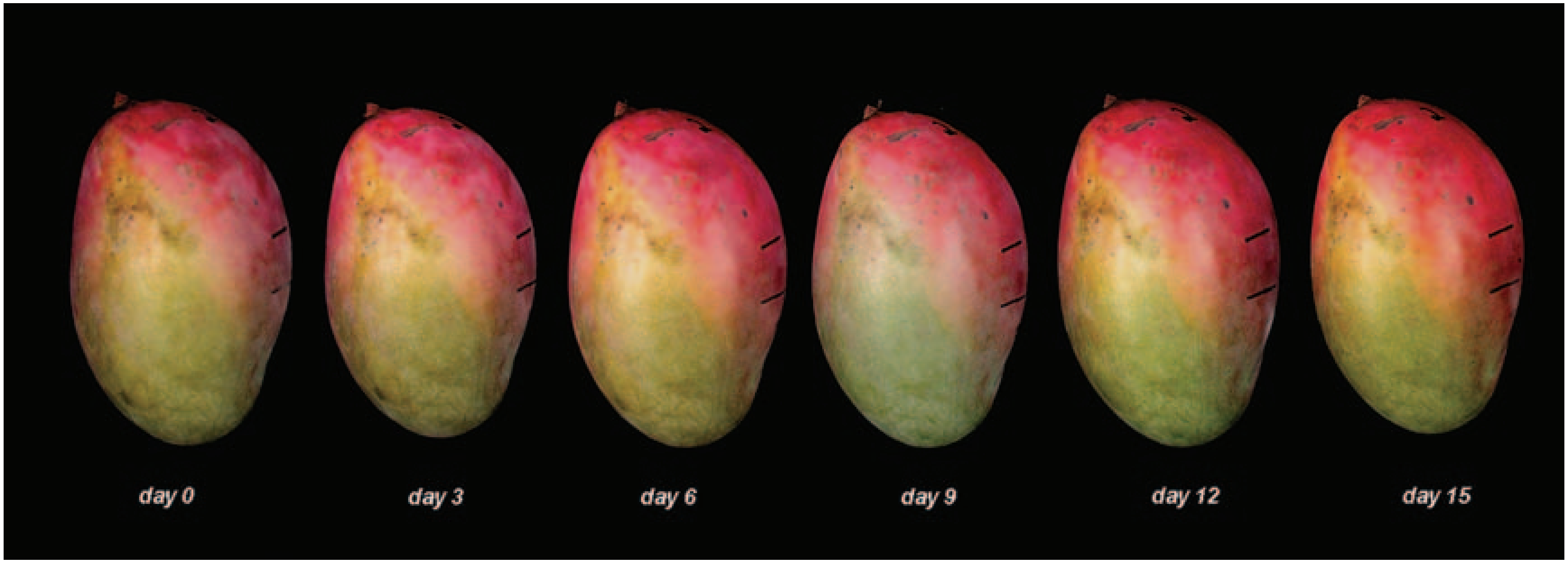

Figure 1.27. Appearance of 'Palmer' mango stored for 15 days at 5°C. After 15 days fruit shows very subtle signs of chilling injury such as small pits and discoloration.

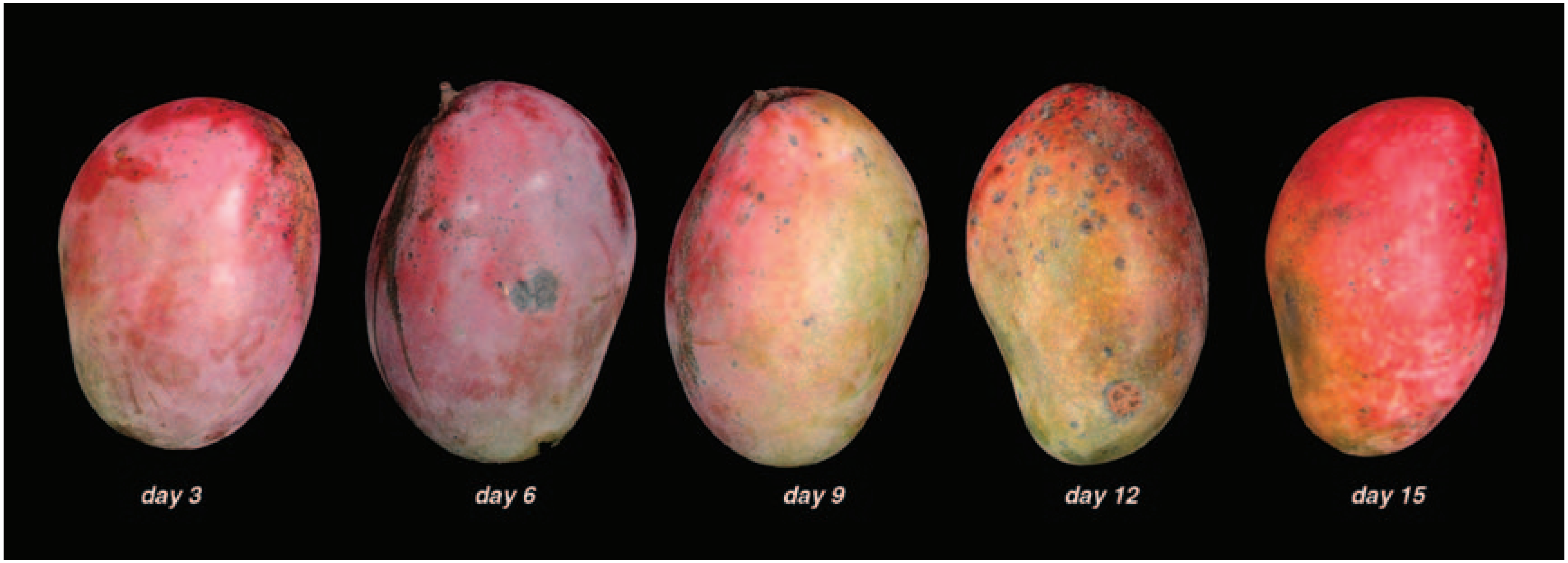
day 3
day 6
day 9
day 12
day 15

Figure 1.28. Chilling injury in 'Palmer' mango after storage at 5°C plus transfer for 2 days at 20°C. Fruit develops discoloration, scalding, pitting, uneven ripening, and decay after transfer to 20°C for 2 days.

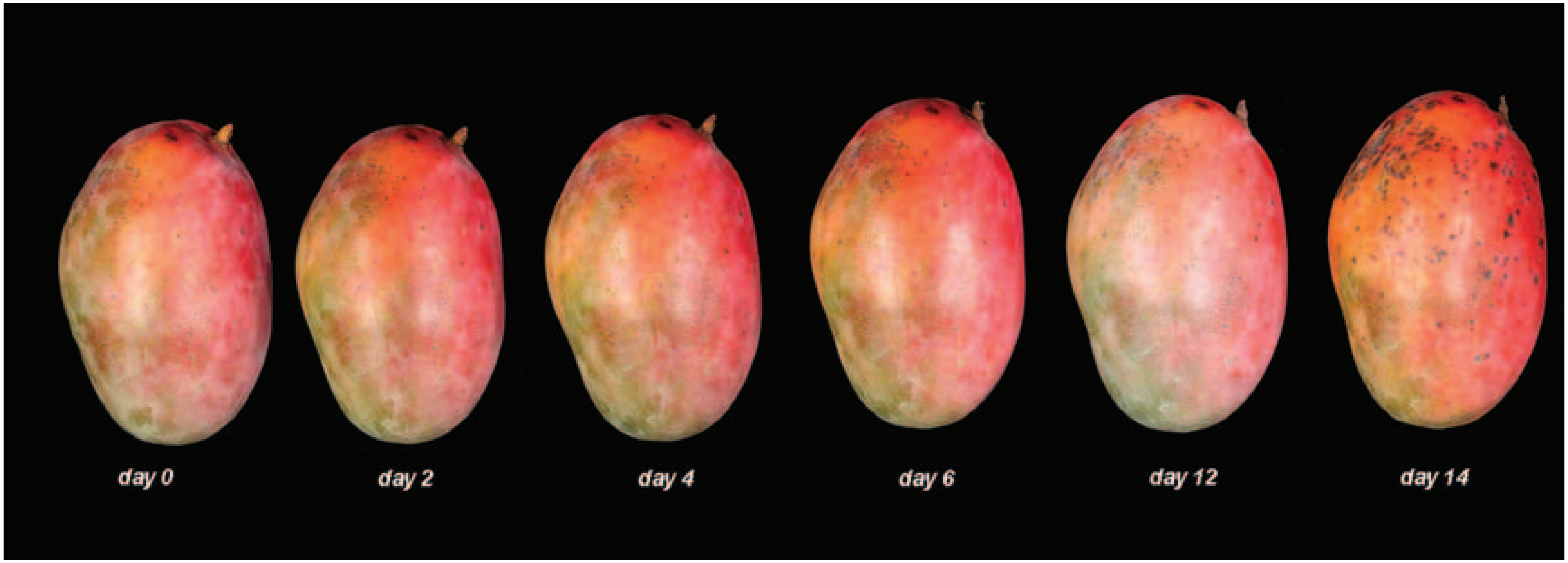
day 0
day 2
day 4
day 6
day 12
day 14

Figure 1.29. Appearance of 'Palmer' mango stored for 14 days at 12°C. Fruit shows acceptable visual quality during 12 days. After 12 days, the fruit is soft and decay starts to be objectionable.

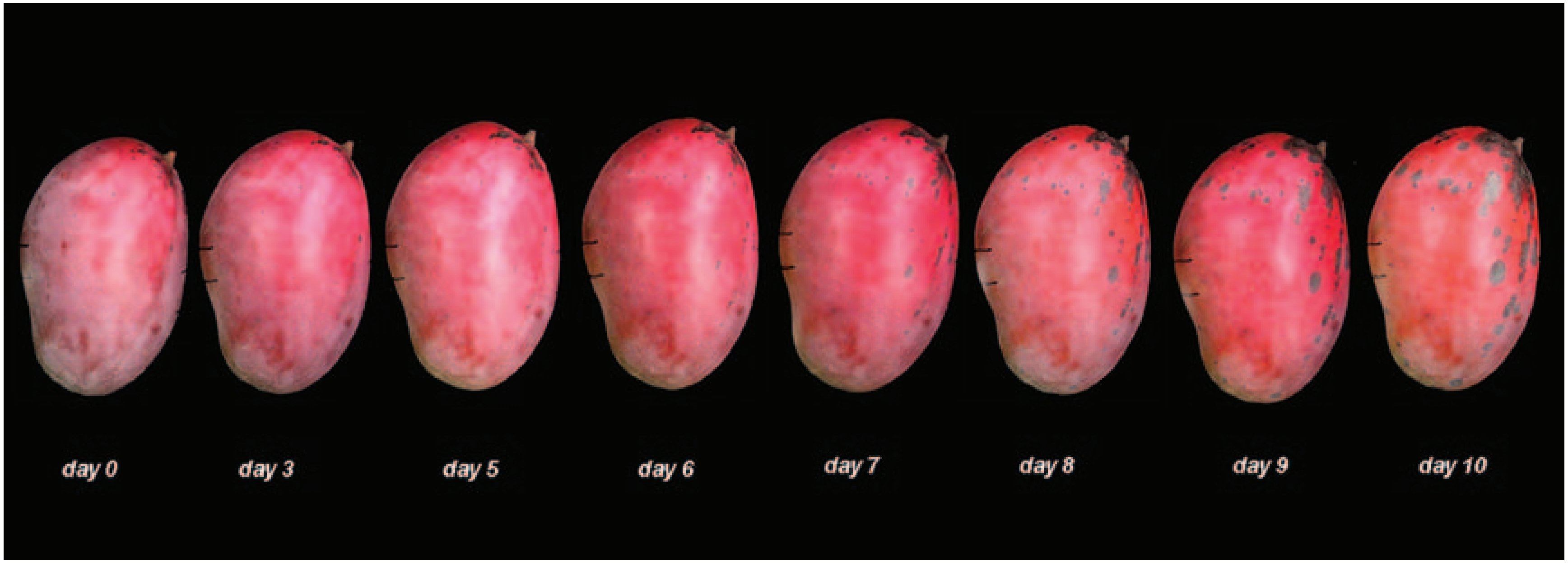
day 0
day 3
day 5
day 6
day 7
day 8
day 9
day 10

Figure 1.30. Appearance of ‘Palmer’ mango stored for 10 days at 15°C. Fruit shows acceptable appearance during 5 days. After 5 days, decay increases and becomes objectionable after 9 days.

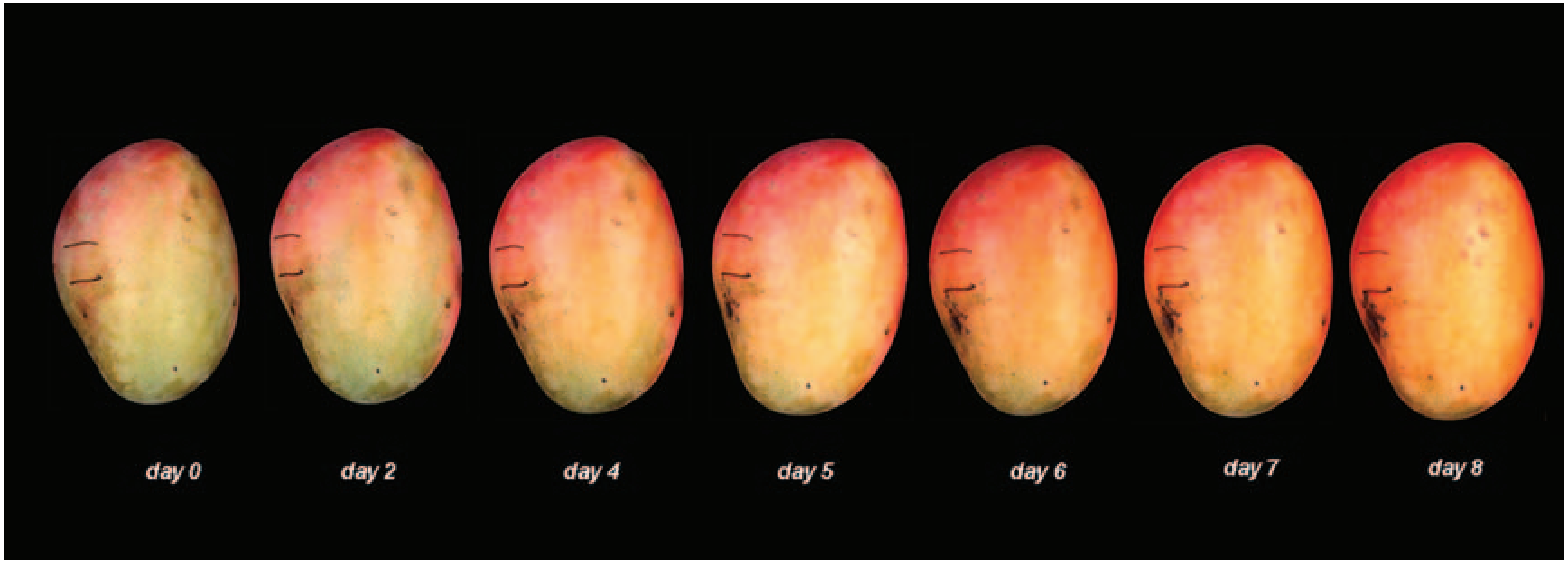
day 0
day 2
day 4
day 5
day 6
day 7
day 8

Figure 1.31. Appearance of ‘Palmer’ mango stored for 8 days at 20°C. Fruit maintains acceptable visual quality during 4–5 days and is completely ripe after 6 days.

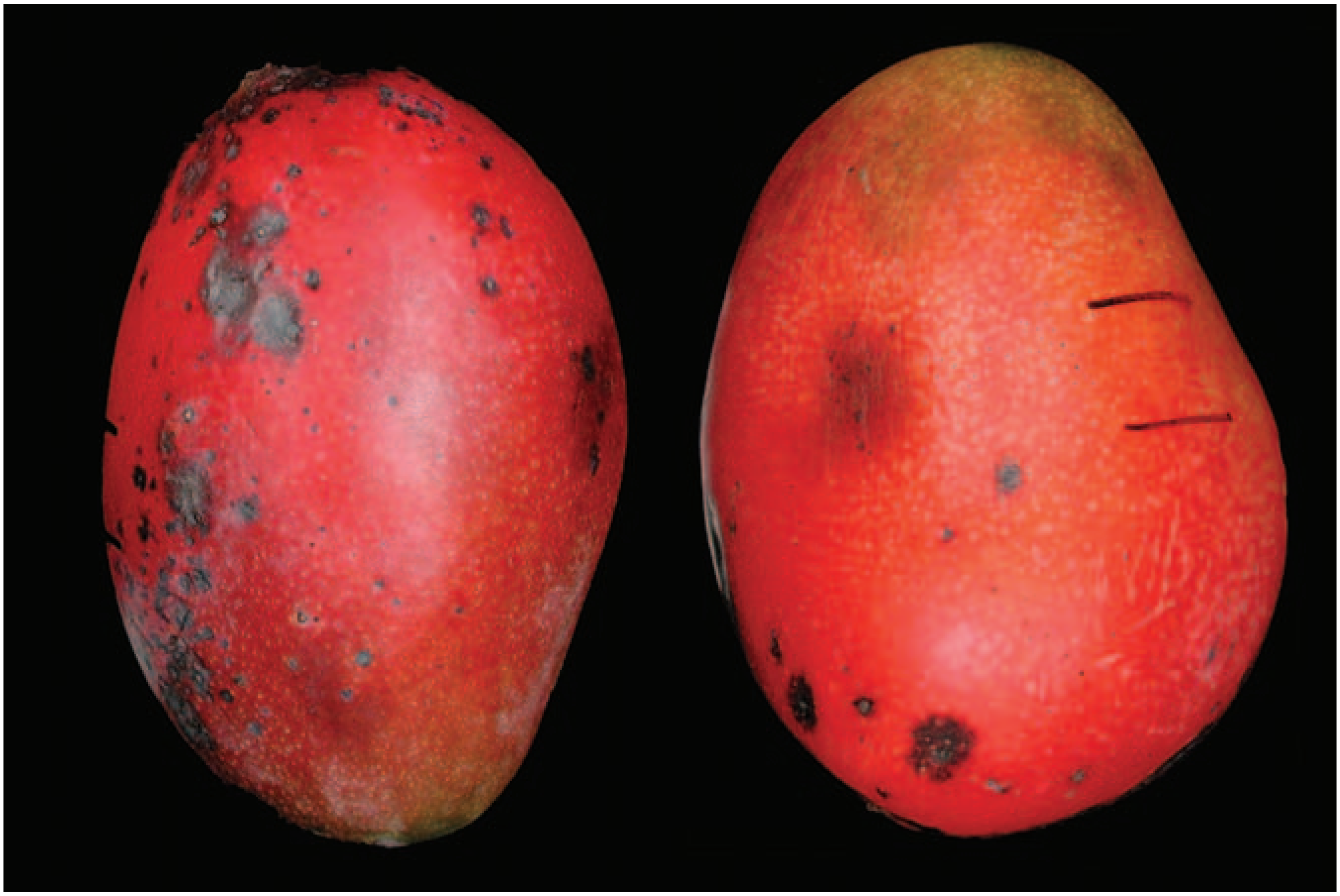

Figure 1.32. Decay (left and right) and shriveling (right) in 'Palmer' mango after 8 days at 20°C.

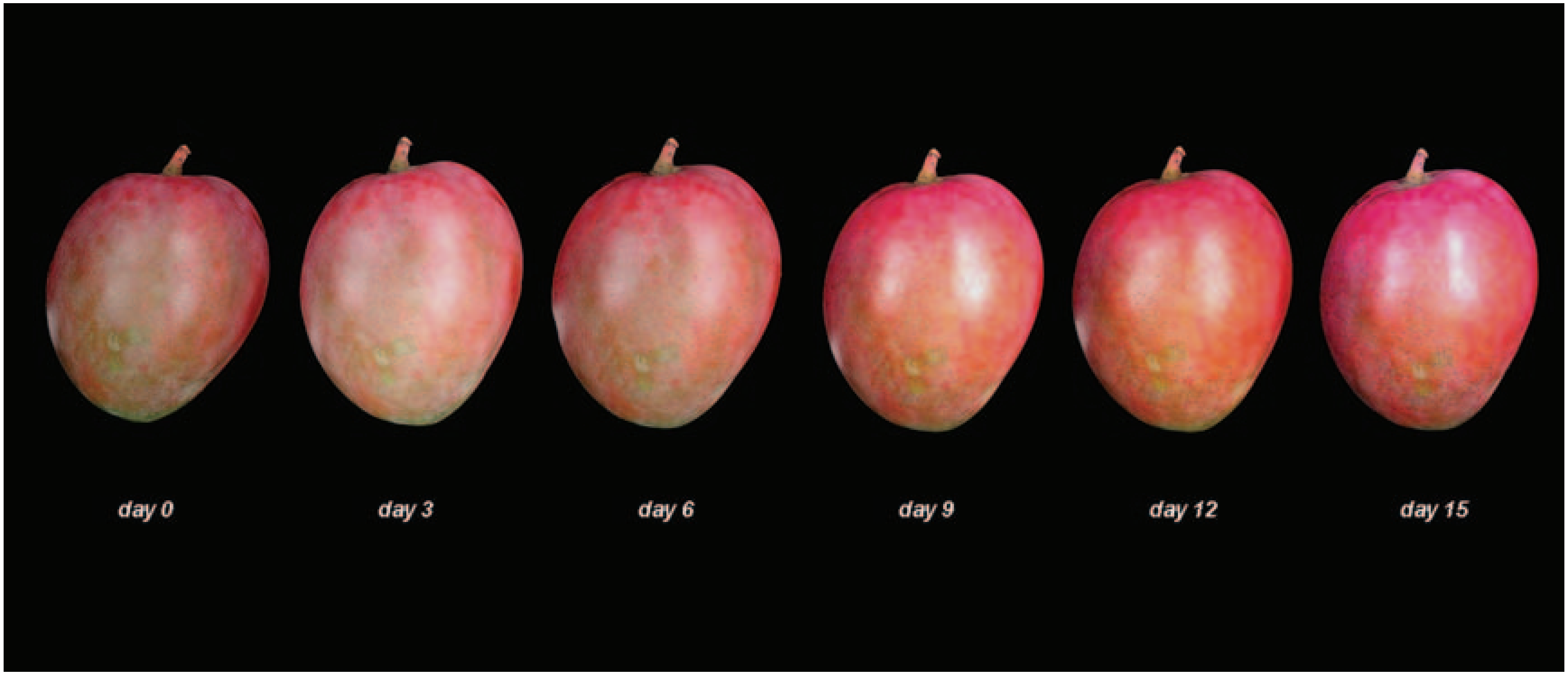
day 0
day 3
day 6
day 9
day 12
day 15

Figure 1.33. Appearance of ‘Tommy Atkins’ mango stored for 15 days at 2°C. After 9 days slight pitting of the skin becomes apparent.

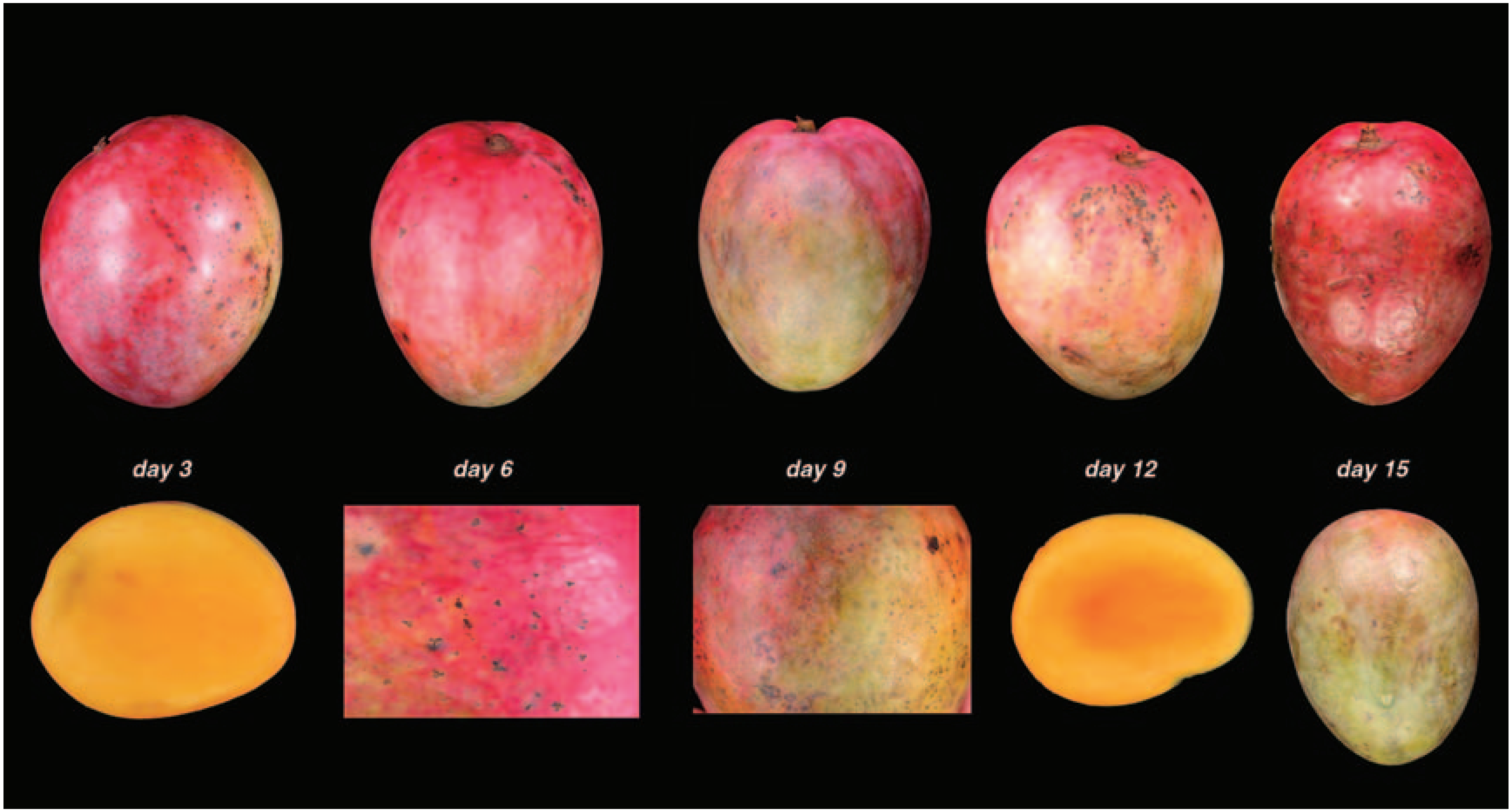

Figure 1.34. Chilling injury symptoms in 'Tommy Atkins' mango after storage at 2°C plus transfer for 2 days at 20°C. Slight water-soaking (after 3 days), pitting and decay (after 6 days), grayish scalding and pitting (after 9 days), water-soaking (after 12 days).

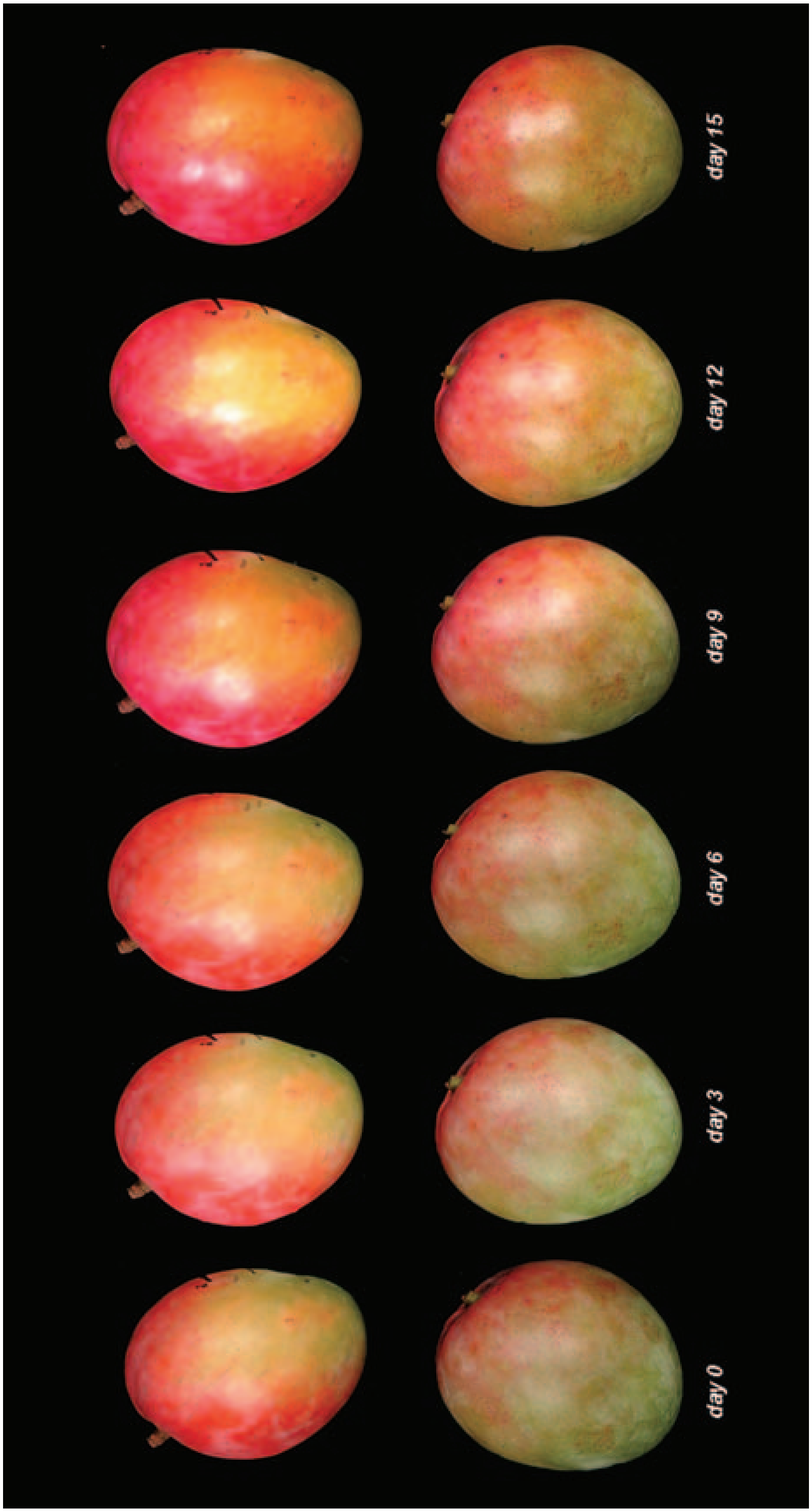
day 0
day 3
day 6
day 9
day 12
day 15

Figure 1.35. Appearance of 'Tommy Atkins' mango (both sides of the fruit) stored for 15 days at 5°C. After 15 days fruit shows very subtle signs of chilling injury such as small pits and discoloration.

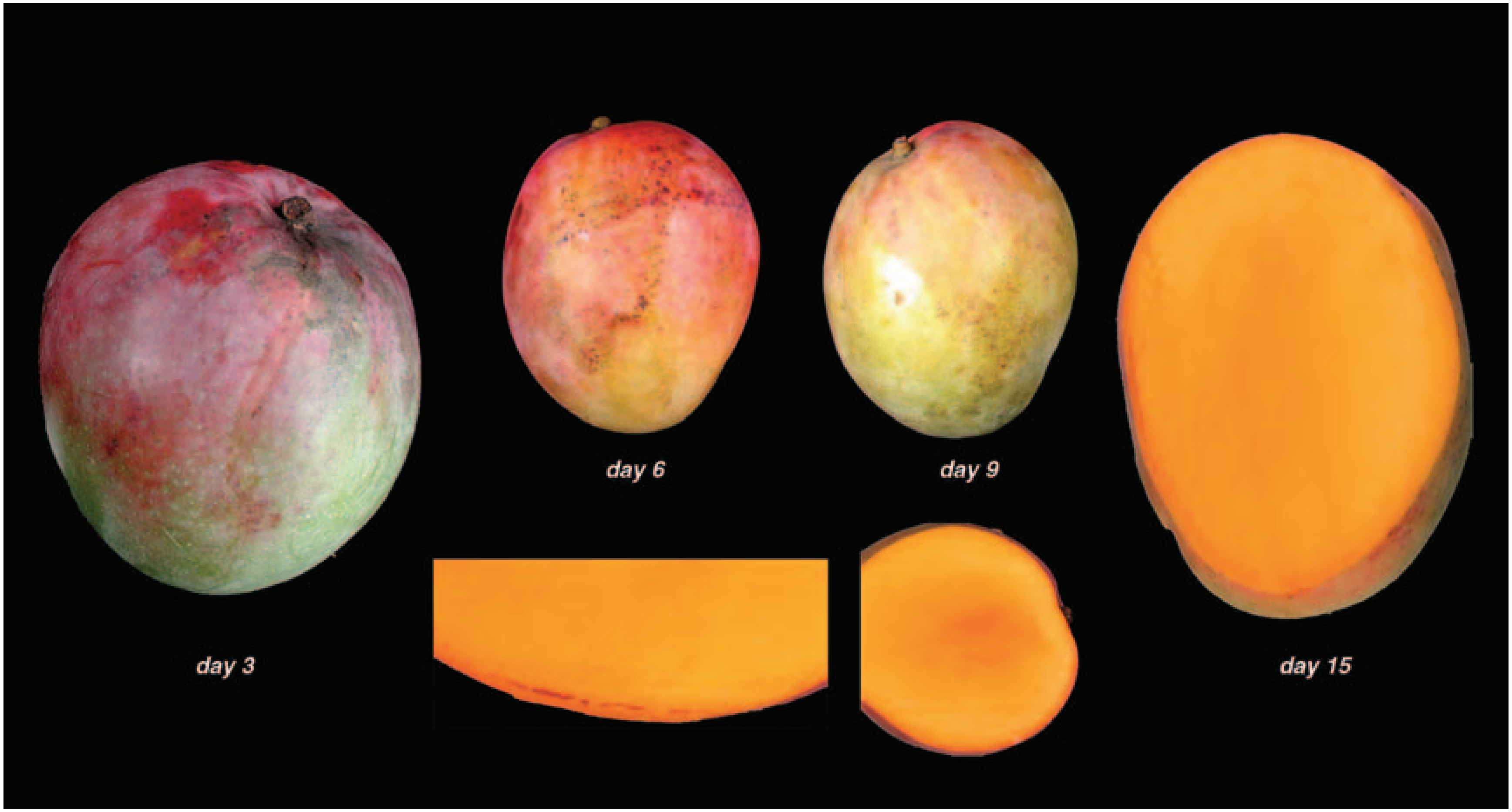

Figure 1.36. Chilling injury in 'Tommy Atkins' mango after storage at 5°C plus transfer for 2 days at 20°C. Fruit develops discoloration, scalding, and uneven ripening after transfer to 20°C. Water-soaking of the flesh is evident after 6 days at 5°C plus 2 days at 20°C.

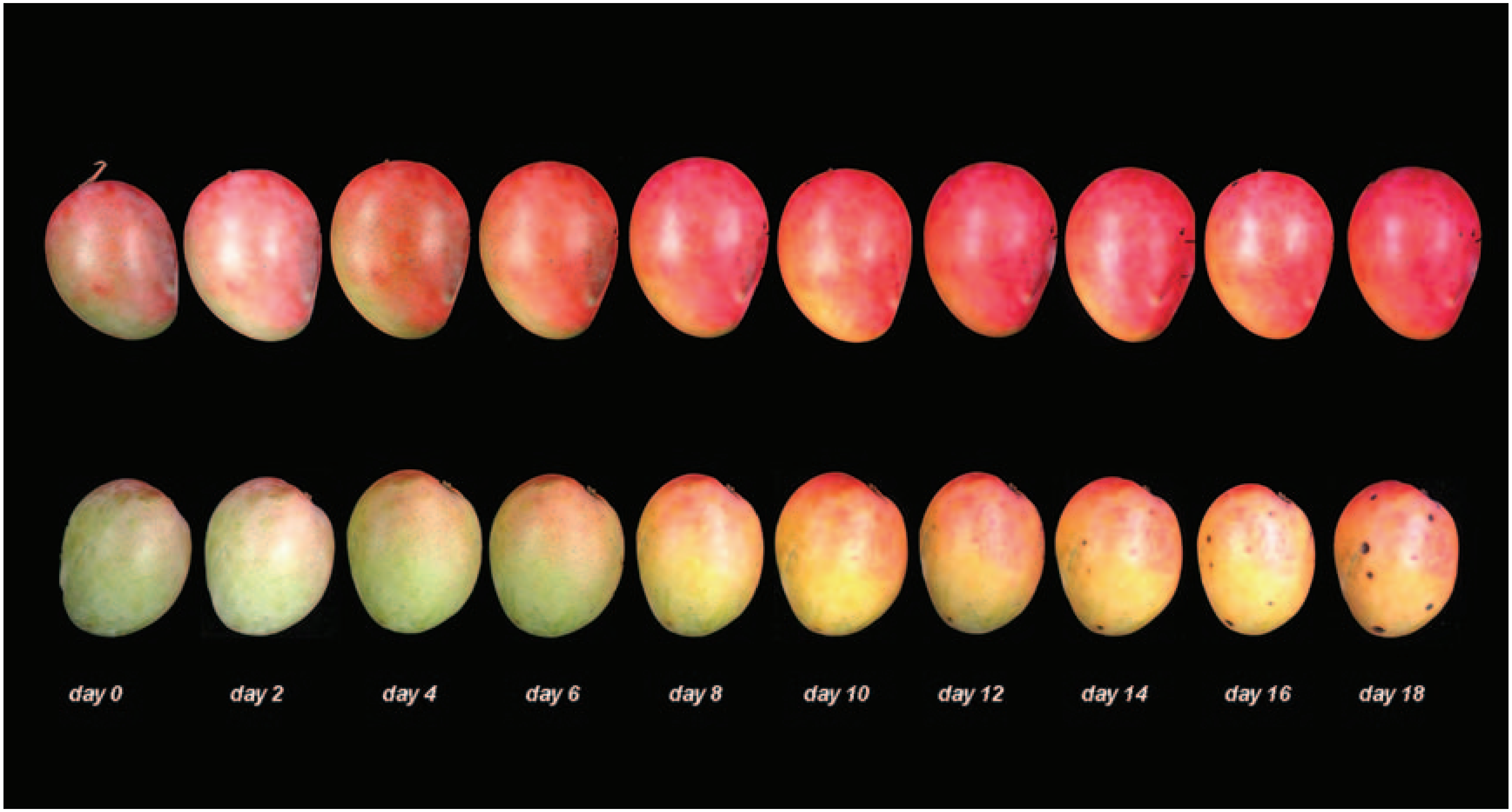
day 0
day 2
day 4
day 6
day 8
day 10
day 12
day 14
day 16
day 18

Figure 1.37. Appearance of 'Tommy Atkins' mango (both sides of the fruit) stored for 18 days at 12°C. Fruit shows acceptable visual quality during approximately 12 days. After 12 days decay develops on the fruit surface and after 18 days the fruit appears completely ripe with no trace of green color.

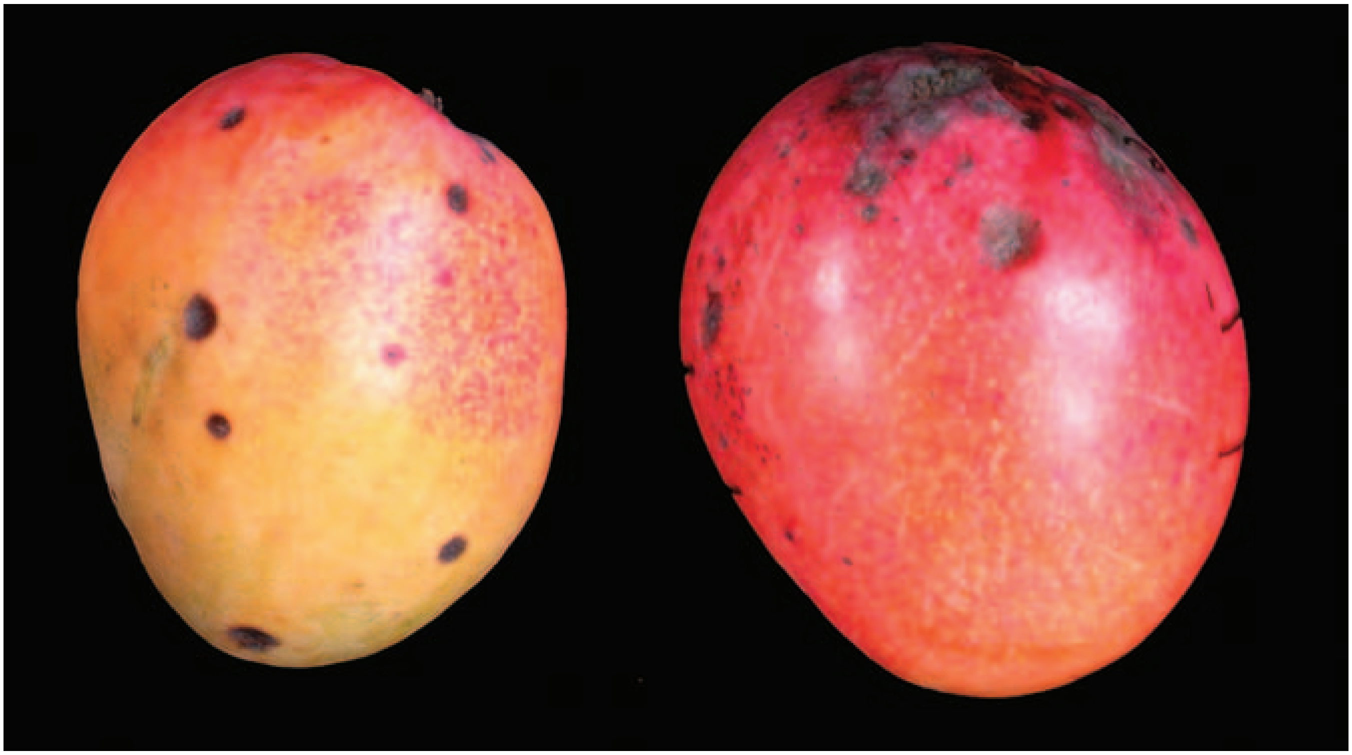

Figure 1.38. Decay in 'Tommy Atkins' mango stored for 18 days at 12°C.

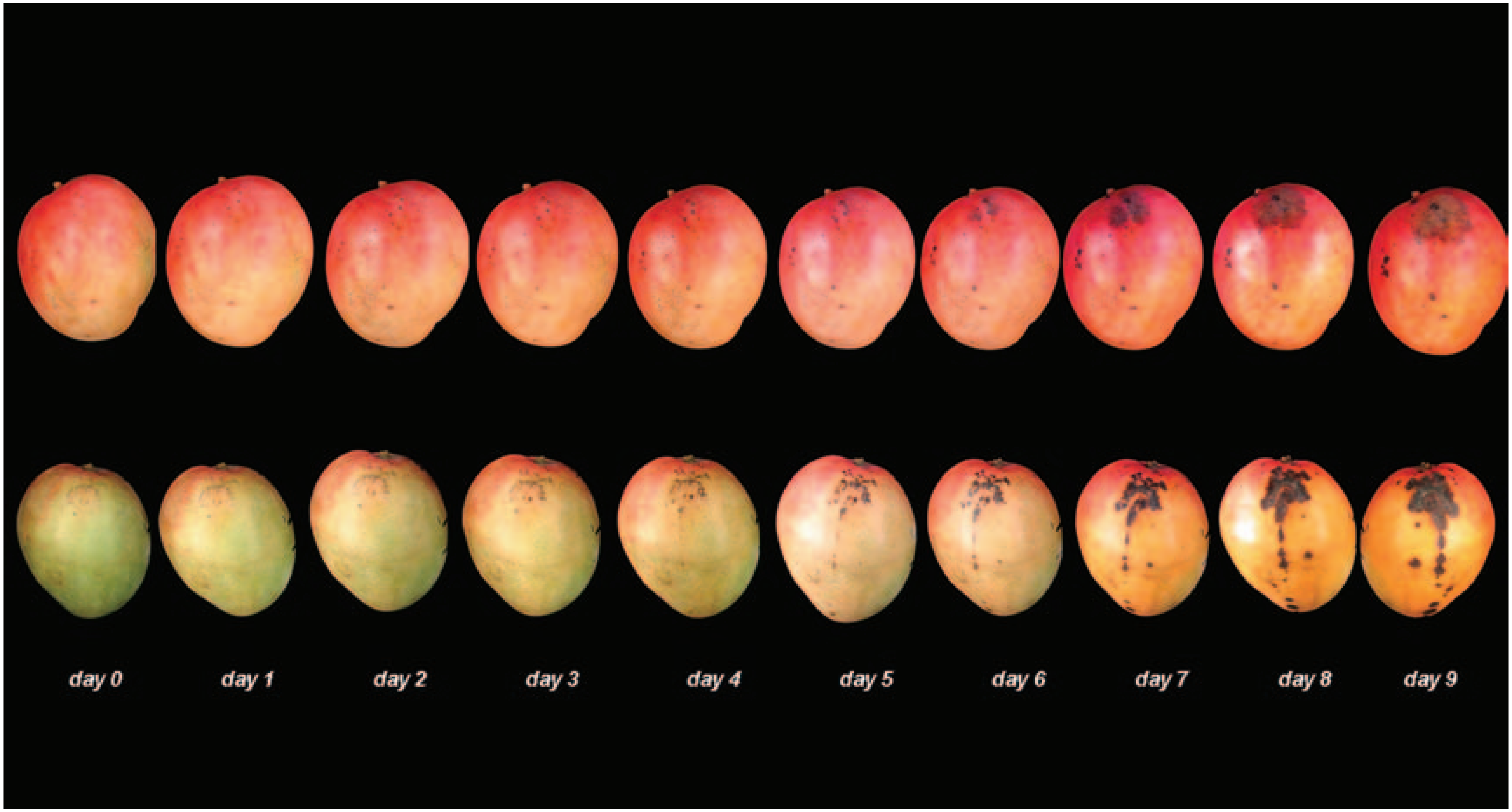
day 0
day 1
day 2
day 3
day 4
day 5
day 6
day 7
day 8
day 9

Figure 1.39. Appearance of 'Tommy Atkins' mango (both sides of the fruit) stored for 9 days at 15°C. Fruit shows acceptable appearance during 2–3 days. After 3 days decay increases and after 9 days becomes objectionable.

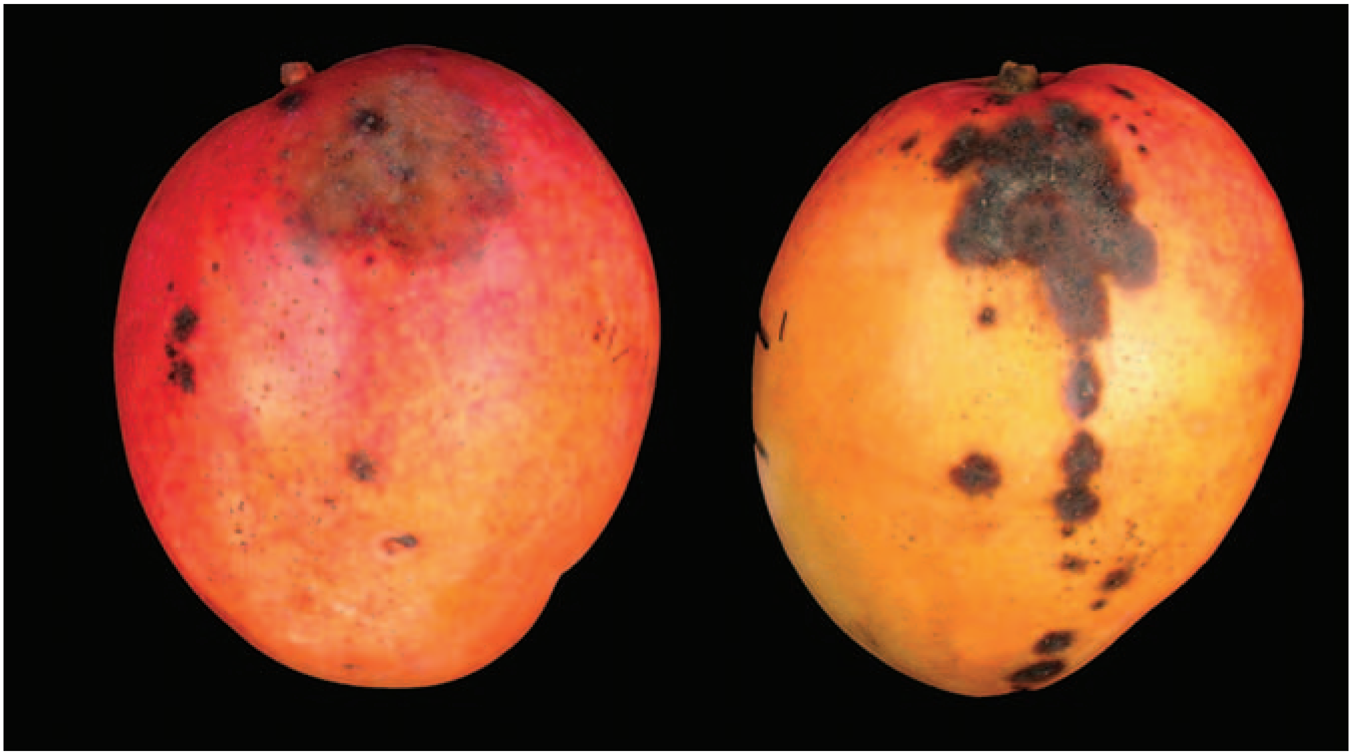

Figure 1.40. Decay in 'Tommy Atkins' mango after 9 days at 15°C.

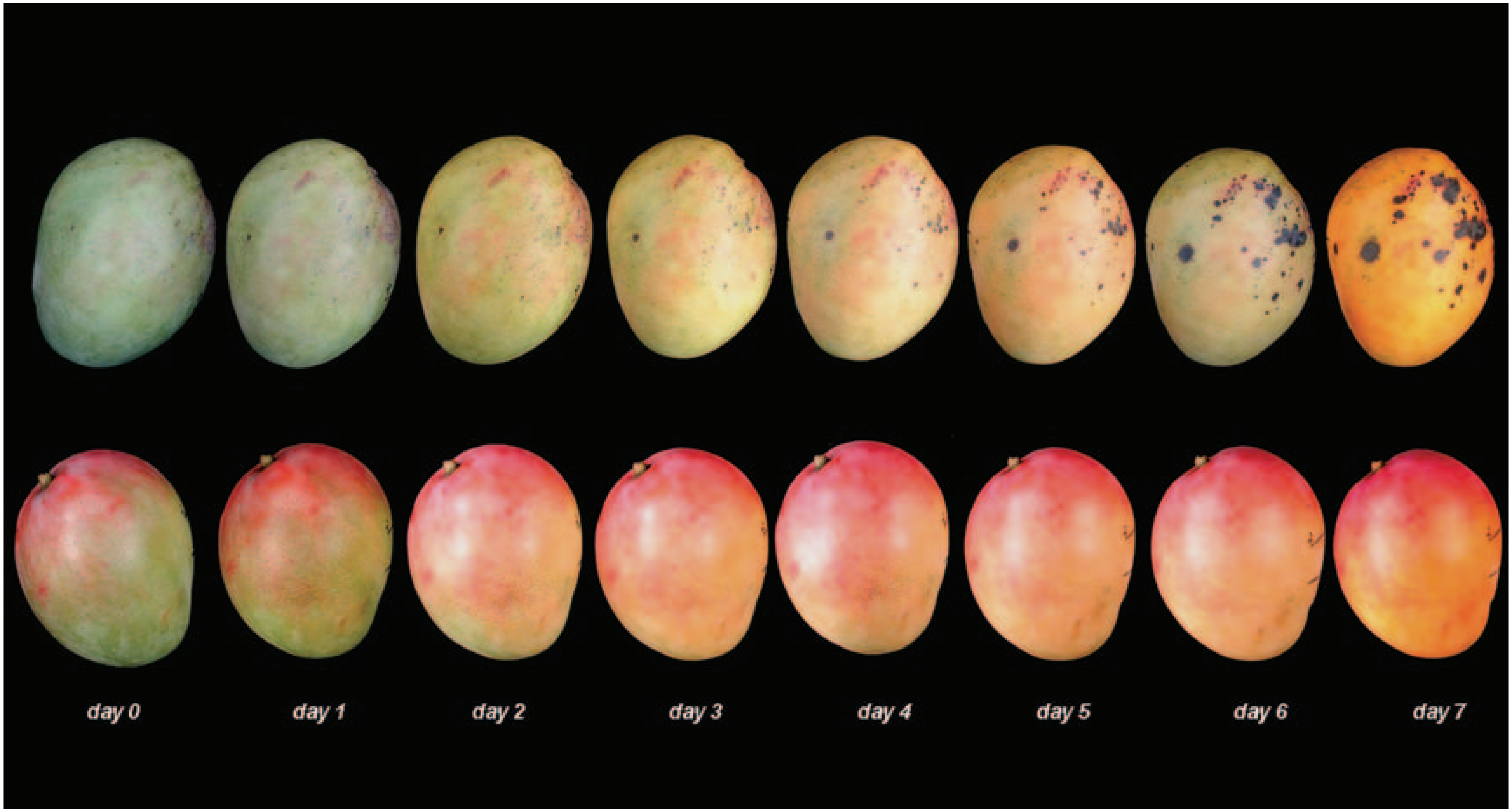
day 0
day 1
day 2
day 3
day 4
day 5
day 6
day 7

Figure 1.41. Appearance of 'Tommy Atkins' mango (both sides of the fruit) stored for 7 days at 20°C. Fruit maintains acceptable visual quality during 2–3 days. After 6 days the fruit is completely ripe and decayed. Softening becomes objectionable after 7 days at 20°C.

PAPAYA

Scientific Name: *Carica papaya*
Family: Caricaceae

Quality Characteristics

When ripe, papaya fruit has an attractive pulp color, flavor, juiciness, and characteristic aroma. The ripe fresh fruit is eaten raw, whereas the unripe fruit is commonly used as a vegetable for cooking. The skin of the fruit is smooth and thin, shading from green to deep orange or to yellow when ripe. In general, as papaya ripens, chlorophyll content decreases, whereas carotenoid content increases, resulting in changes of skin color from green to yellowish-orange (Bron et al. 2004). The color of the flesh is greenish-white in immature fruit, changing to pale orange-yellow, salmon, pink, or red during ripening, depending on the cultivar. Papayas are usually harvested at color break (i.e., showing some skin yellowing) to 25% yellow for export or at 50–75% yellow for local markets. However, the higher the percentage of yellow color in the skin of papaya fruit the better the eating quality after ripening (Nakasone and Paull 1998).

The first yellow string appears in solo-type papayas by 145 days after anthesis and parallels an increase in soluble solids content. At this point, papaya coloration is at least 6% and the soluble solids content reaches 11.5%. By 168 days after anthesis, the fruit surface is predominantly yellow, indicating conclusion of fruit ripening, and the soluble solids content reaches 15% (Calegario et al. 1997). Hawaiian grade standards require the solo-type papaya to have 11.5% total soluble solids content when harvested, which corresponds to the color-break stage, and that no more than 5% by count in the lot have a soluble solids content less than 10.5% (Nakasone and Paull 1998; Sankat and Maharaj 1997; Zhou et al. 2005). Soluble sugars accumulate mainly when the papaya fruit is still attached to the plant, and as the fruit ripens starch decreases from about 0.13% in green fruits to about 0.06% in ripe fruit (Gomez et al. 2002). Therefore, fruit harvested immature does not ripen well and contains low total soluble solids that result in tasteless fruit (Thompson 2003). Papayas harvested at the mature-green stage were described to have a characteristic green papaya aroma, whereas fruit in intermediate and ripe stages was described as having a marked aroma of ripe papaya. Changes in the aroma of papaya fruit during ripening were related not only to an increase in sugar content and a decrease in acidity but also to an increase in the phenolic content and a decrease in latex levels. Latex imparts a bitter taste and is characteristic of green papaya (Gomez et al. 2002). Consequently, papayas with high soluble solids content (higher than 10%) are usually more desirable than greener fruit with lower sugar content to eat as dessert (Imungi and Wabule 1990).

Papaya fruit contains about 88.8% water, 9.8% carbohydrates, 0.6% proteins, and 1.8% fiber (USDA 2006). Papaya fruit is very rich in vitamins, especially in vitamin C, contributing from 50 to 200% of the Recommended Daily Allowance for this vitamin per 100 g of fresh fruit (National Academy of Sciences 1989). Ripe papaya may contain an average 62 mg of vitamin C and 284 IU of vitamin A per 100 g of fresh fruit (USDA 2006).

Optimum Postharvest Handling Conditions

The optimum temperature during handling (i.e., storage, shipping, or display) of papaya fruit depends on the type of cultivar, maturity at harvest, and length of exposure to that temperature. If adequately handled, papayas may be expected to have a postharvest life of 4–6 days under ambient tropical conditions (25–28°C), or up to 3 weeks under lower temperatures (10–12°C) (Paull et al. 1997). In general, color break to 25% yellow papayas can be stored at 13°C; partially ripe fruits (25–50% yellow) can be stored at 10°C; and ripe fruit (more than 50% yellow) can be stored at 7.5°C (Desai and Wagh 1995; Thompson 2003). When the marketing period of papaya is at least 7 days after harvest, holding mature-green fruit at temperatures lower than 15°C should be avoided, since this may result in a fruit with objectionable quality upon ripening and reduced proportion of fruit that ripens (Wills and Widjanarko 1997). Although papaya can be ripened at temperatures between 20 and 25°C for the retail market, temperatures above 32°C may cause delayed ripening, rubbery pulp texture, and fruit-surface bronzing (An and Paull 1990). The relative humidity should be maintained from 90 to 95% throughout postharvest handling.

Temperature Effects on Quality

Appearance of papaya fruit is limited by accelerated ripening, yellowing, and decay when fruit is stored at temperatures higher than 15°C. High storage temperatures may also hasten water loss and, consequently, shriveling and softening of the fruit, whereas storage of papaya fruit at temperatures lower than 15°C may result in CI.

The severity of symptoms caused by exposure of papaya fruit to chilling temperatures is dependent not only on the temperature but also on the cultivar, the maturity of the fruit at harvest, and the length of exposure to that temperature (Chan 1988; Chen and Paull 1986; El-Tomi et al. 1974). In general, symptoms of CI in papayas include pitting of the skin, scald, hard lumps in the pulp around the vascular bundles, water soaking of the flesh, abnormal ripening with blotchy discoloration, and increased susceptibility to decay (Ali et al. 1993; Chan et al. 1985; Chen and Paull 1986; Thompson and Lee 1971). Meticulous evaluation of CI symptoms on the skin of mature-green solo-type papaya showed the development of dark olive spots of 1–2 mm in diameter that in severe injury coalesced and formed scald-like areas. Mild bruises became more evident during ripening and appeared as green areas sometimes surrounding a pitted area of the skin, giving the fruit a blemished appearance. In more yellow fruit, development of light brown spots that frequently coalesced was associated with collapsed tissue. At the mature-green stage, internal CI symptoms were hard white areas that do not soften upon transfer to ripening temperatures. Off-flavor and odors usually accompanied skin and tissue injury of severely chilled fruit (Chen and Paull 1986).

Less mature papaya fruit are in general more predisposed to develop CI symptoms when handled at temperatures below 15°C. For example, in mature-green ‘Kapoho Solo’ papayas, CI symptoms developed following storage at 22°C in fruit previously stored for 7 days at 0°C, for 10 days at 2°C, and after 20 days at 7.5°C. After transfer to 24°C, color-break Hawaiian papayas previously stored at 5°C for 4 days showed a dull, dark olive discoloration appearing on the equatorial surface of the fruit (Chan et al. 1985). However, ‘Kapoho Solo’ papayas harvested showing 60% yellowing could be stored at 2°C for 17 days without developing CI symptoms (Chen and Paull 1986). Storage at 10°C for 20 days of ‘Exotica’ papayas harvested 5% yellow completely inhibited the development of peel color but not the decrease in firmness. However, after transfer to 25°C following storage at 10°C for 5, 10, and 15 days color developed faster, whereas fruit firmness significantly decreased (Ali et al. 1993). Nazeeb and Broughton (1978) reported that mature-green ‘Bentong’ and ‘Taiping’ papayas from Malaysia developed CI after storage for 7 days at 15°C. When stored at temperatures between 5 and 17°C during 21 days, Australian mature-green papayas did not attain 100% ripening (i.e., full yellow color) compared to fruit stored at 20°C. Therefore, after 21 days fruit stored at 5, 10, 12.5, and 15°C showed only 50, 50, 70, and 80% skin yellow color development, respectively, whereas fruit stored at 17 or 20°C reached 100% full yellow color after the same period and showed no signs of CI. In addition, the total time for fruit to ripen increased with decreasing storage temperature, and fruit stored at lower temperature failed to ripen because of the prior development of tissue collapse and decay (Wills and Widjanarko 1997). Like the Australian and Malaysian cultivars, the sensitivity to CI of the large-fruited papaya cultivars grown in southern Florida seems to be greater than that of the more common solo-type Hawaiian cultivars (Nunes et al. 2006).

Pre-storage heating and intermittent warming have been used to alleviate CI in papayas stored at low temperatures. For example, exposure of papaya fruit to 42°C for 6 hours before storage at 5°C resulted in reduced CI symptoms (Huajaikaew et al. 2005). Intermittently warmed papaya (warmed at 15 or 20°C for 3 days, then held at 5°C for 2 days) developed slighter CI symptoms, whereas fruit stored continuously at 5°C showed a greater extent of pitting and remained unripe when transferred to ambient temperature. Furthermore, papaya kept at 5°C developed CI symptoms faster and more severely than intermittently warmed fruit. Fruit intermittently warmed at 20°C had a higher yellow index than fruit intermittently warmed at 15°C (Huajaikaew et al. 2000).

The rate of skin yellowing in papaya fruit shows a linear relationship with storage temperature (An and Paull 1990). Therefore, the higher the storage temperature the faster the color changes from green to yellow or orange. Hue of ‘Exp. 15’ papayas stored at 15 and 20°C decreased during storage but remained quite stable in papayas stored at lower temperatures. Decrease in hue value from about 115–80° corresponds to changes in the superficial color from a yellowish-green to a yellowish-orange color, exactly as the visual changes observed in ‘Exp. 15’ papaya fruit during storage (Proulx et al. 2005). Although after 6–8 days at 10°C the color of papaya ‘Exp. 15’ began to change from green to greenish orange-yellow, meaning that fruit was able to ripen at this temperature, ripening was not uniform and the fruit showed green spots among the yellowish-orange color when transferred to ambient temperatures. In fact, the L* values of papayas stored at 0, 5, and 10°C did not change much during storage when compared to L* values of papayas stored at 15 and 20°C, which increased during storage. This was possibly because papayas stored at chilling temperatures were not able to ripen evenly, whereas after 4 days at 20°C papayas were completely yellowish-orange (Proulx et al. 2005). Lam (1990) pointed out that papaya fruits affected by CI do not change their color indices (i.e., L*, hue, or chroma) even when transferred to 25°C from cold storage. However, papayas stored at 15°C for 14 days and then transferred to 25°C would ripen normally. This could explain the fact that color indices of papayas stored at 0, 5, and 10°C did not change considerably during storage, and after transfer to 20°C the fruit maintained a dull greenish color and did not show a normal ripening pattern (Proulx et al. 2005).

Exposure to high temperatures (i.e., above 30°C), for extended periods, normally used to control pests and diseases of papaya fruit, may also cause detrimental effects to quality. Hard lumps, irregular ripening, pitting of the epidermis, flesh becoming soft and translucent, cooked flavor, objectionable odor, blackening of vascular bundles, and increased incidence of some diseases are the most common symptoms observed in overheated papayas (Lay-Yee et al. 1998; Nishijima 1995; Nishijima et al. 1992; Paull and Chen 1990). Hot-air (48.5°C for 3–4 hours) treated papaya was associated with an increase in the incidence of internal lumpiness when compared to nonheated fruit (Nishijima et al. 1992). In addition, compared to nonheated fruit, papayas exposed to 48.5 or 49.5°C for more than 60 minutes developed skin scalding, had increased mass loss, were less firm, and developed off-flavor during ripening (Lay-Yee et al. 1998). Exposure of papaya fruit to hot moist air at 48.5–50°C and 100% humidity for 4 hours increased the fruit temperature and resulted in severe injury compared to dry air (50% humidity) at the same temperature. Therefore, during subsequent storage at 5°C, hot–dry air–heated papayas showed less sensitivity to CI and accumulated more sugars compared to nonheated fruit, whereas internal color, soluble solids content, weight loss, and carotene and lycopene concentrations were similar in heated and nonheated fruits (Pérez-Carrillo and Yahia 2004). Nishijima (1995) suggested that the single hot-water dip (49°C for 15 minutes) was the optimum heat treatment, as it controlled diseases with minimal detrimental impact on fruit quality.

In general, weight loss due to loss of moisture from papaya fruit increases during storage. Furthermore, slightly riper fruit may lose more weight compared with less ripe fruit, when handled likewise (Proulx et al. 2005). Paull and Chen (1989) suggested that the major pathway for weight loss in papayas was mainly water lost through the stem scar, the stomata, and the cuticle. Consequently, the amount of water lost by a papaya fruit may differ depending on the cuticle thickness, which is in turn cultivar and maturity dependent. This fact might explain the greater weight loss by riper papayas compared to less ripe fruit during storage at different temperatures (Proulx et al. 2005). According to Paull and Chen (1989), the loss of approximately 8% of the initial weight from ‘Sunset’ and ‘Sunrise’ mature-green papayas results in “rubbery” texture, low gloss, slight to moderate skin shrivel, and nonsaleable fruit. However, ‘Exp. 15’ papayas developed objectionable softening of the flesh, overripe appearance, and severe shriveling when weight loss attained 4.5% (Nunes and Emond 2007).

Chemical composition of papayas changes during storage, regardless of the storage temperature. However, no significant difference was observed in the acidity of the fruit stored at temperatures between 0 and 20°C (Maharaj and Sankat 1990; Proulx et al. 2005). Depending on the cultivar and maturity at harvest, the soluble solids content of papaya ranged from 5 to 19% at the time of harvest (Paull et al. 1997; Proulx et al. 2005). However, compared to initial values, decreases in the soluble solids content of papaya ‘Exp. 15’ after 6 days at 20°C was greater than that of fruits stored for 14 days at 0°C (about 36 and 25%, respectively).

Papaya is considered to be a good source of ascorbic acid (vitamin C), and depending on the type of cultivar and ripeness stage, the ascorbic acid content may range from 47 to 72 mg per 100 g fruit fresh weight in green papaya, and from 80 to 145 mg per 100 g fruit fresh weight in half-ripe papaya (Firmin 1997; Imungi and Wabule 1990; Pal et al. 1980; Proulx et al. 2005). However, ascorbic acid content of papaya fruit tends to decrease during storage, regardless of the storage temperature (Nazeeb and Broughton 1978; Nunes et al. 2006; Proulx et al. 2005). Papaya ‘Exp. 15’ stored at 0, 5, 10, 15, and 20°C showed about 48, 36, 42, 41, and 43% reduction in ascorbic acid content, respectively, after approximately 14 days of storage. Greatest decrease in ascorbic acid content was, therefore, observed in fruit stored at 0°C. That is, ascorbic acid of papaya ‘Exp. 15’ decreased from 750 to 393 mg per 100 g fruit dry weight after 14 days at 0°C (Proulx et al. 2005). Two main factors appear involved in the loss of ascorbic acid during storage: the maturity of the fruit at harvest and the temperature during storage. Even though riper fruit tended to have higher ascorbic acid content than less ripe fruit at harvest, losses during storage were more pronounced in the riper fruit than in the less ripe fruit (Nunes et al. 2006). The overripeness of the fruit might have contributed to a greater decrease in ascorbic acid content compared with less ripe fruit. Furthermore, the softening of fruit, caused by the alteration of the cell-wall structure and decrease in cell-wall strength due to ripening (Paull et al. 1999), might promote the release of ascorbate oxidase that is normally bound to the cell walls, and thereby allow exposure of ascorbic acid to oxidation (Loewus and Loewus 1987; Nobile and Woodhill 1981). Exposure of papaya fruit to temperatures of around 20°C may, however, result in a slight increase in the ascorbic acid content of the fruit (Giri et al. 1980; Proulx et al. 2005). It was also previously suggested that the increase in total ascorbic content during storage of fruit and vegetables might be attributed to the synthesis of ascorbic acid from monosaccharides, since in plants most synthesis starts with preformed D-glucose (Liao and Seib 1988; Loewus and Loewus 1987). In papaya fruit exposed to chilling temperatures during handling or storage, losses of ascorbic acid are greater than those in fruit handled at nonchilling temperatures (Nunes et al. 2006). Decreases in the ascorbic acid content of papaya fruit exposed to chilling temperatures were probably due to the same degenerative process of the cell-wall structure that usually takes place during ripening. That is, the damage in the cell membranes that generally occurs during exposure of chilling-sensitive fruits to cold temperatures may be compared to that occurring during senescence and thus might have also contributed to accelerated ascorbic acid oxidation (Marangoni et al. 1996).

Time and Temperature Effects on the Visual Quality of ‘Exp. 15’ Papayas

‘Exp. 15’ papayas (large, early season, red-fleshed fruit similar to ‘Red Lady’) shown in Figures 1.42–1.51 were harvested at color break (some skin yellowing) to 25% color, from a commercial operation in Homestead, Florida, during the spring season (i.e., April–May). Promptly after harvest, fresh papaya was stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 85–98% relative humidity.

Changes in the color of 'Exp. 15' papayas from green to fully yellowish-orange and development of decay are the major visual quality changes observed in fruit stored at 15 and 20°C, whereas skin injuries and decay are the most striking changes in the visual quality of papayas stored at chilling temperatures.

Storage of 'Exp. 15' papaya at 0, 5, and 10°C results in the development of CI, and the lower the storage temperature, the shorter the postharvest life of the fruit. Papayas stored at 0°C maintain acceptable visual quality for 12 days, but subtle skin pitting develops after 6 days (Figure 1.42). However, when papayas are stored for more than 4 days at 0°C, CI symptoms aggravate, particularly when the fruit is transferred to ambient temperature. Figure 1.43 shows symptoms of CI in 'Exp. 15' papaya, such as shriveling of the skin and pitting after 4 days of continuous storage at 0°C, followed by severe decay of the pits after transfer of the fruit to 20°C for 2 additional days. As exposure time to 0°C increases the symptoms of CI aggravate. Severe symptoms of CI, such as external and internal water soaking, develop in papayas stored for 12 days at 0°C after transfer to 20°C for 2 days (Figure 1.44). In most cases, the CI symptoms are very subtle during continuous storage at 0°C or even right upon removal from the cold temperature and can be perceived only when the fruit remains 1 or 2 days at ambient temperature. However, Figure 1.45 shows an extreme example of CI in papaya immediately after removal from 0°C and aggravation of the symptoms after transfer to 20°C for 2 additional days. After 14 days of continuous storage at 0°C, the fruit develops severe pitting; mycelium growth is perceptible in some of the pits, whereas scalding and uneven ripening are also evident. After transfer from 0 to 20°C, the pits collapse, and decay develops rapidly and severely affects the entire fruit.

'Exp. 15' papayas stored at 5°C maintain acceptable visual quality for 6–8 days (Figure 1.46). However, after approximately 6 days, CI symptoms, such as subtle surface pitting, become evident. As in papayas stored at 0°C, the symptoms of CI during storage at 5°C aggravate when the fruit is transferred to ambient temperatures. After continuous storage for 10 days at 5°C, small pits develop on the fruit surface. After transfer of these fruits to 20°C for 2 days, darker green scald-like areas develop on the fruit skin, the pits become larger, and mycelium develops on some of the pits (Figure 1.47).

'Exp. 15' papayas stored at 10°C maintain acceptable visual quality during 8–10 days (Figure 1.48). However, after approximately 8 days papayas develop symptoms of CI such as pitting of the skin, which worsens when transferred to ambient temperatures. After continuous storage for 10 days at 10°C, pitting becomes evident on the fruit surface. After transfer to 20°C for 2 additional days pitting aggravates, the fruit develops a scald-like appearance with some areas of water-soaked tissue, and mycelium develops on the collapsed pits (Figure 1.49). Subsequently, the fruit becomes softer and finally collapses owing to cell-wall breakdown, following major water loss.

When stored at 15°C, 'Exp. 15' papayas continue to ripen normally. After 6 days the color changes from a light yellowish-green to a yellowish-orange with slight traces of green, and the fruit maintains acceptable visual quality for 8–10 days (Figure 1.50). However, after approximately 8 days firmness decreases and the fruit becomes soft and shriveled. Decay may also become a problem if papayas are stored for more than 10 days at 15°C.

As observed in papayas stored at 15°C, fruit stored at 20°C continues to ripen normally but at a faster rate than that held at lower temperature. Color of the fruit changes from green with some traces of orange to a deeper orange color, and after 6 days the fruit appears fully orange and overripe (Figure 1.51). Although 'Exp. 15' papaya fruit stored at 20°C maintains an acceptable appearance for about 4 days, after approximately 2 days, papaya firmness decreases and the fruit becomes very soft.

Overall, papaya 'Exp. 15' has a longer postharvest life and maintains a better visual quality when stored at 15°C (10 days), compared to storage at lower or higher temperatures. Papayas stored at 0 and 20°C retain acceptable visual quality for only 4 days, whereas visual quality of fruit stored at 5 and 10°C deteriorates after 6 and 8 days, respectively.

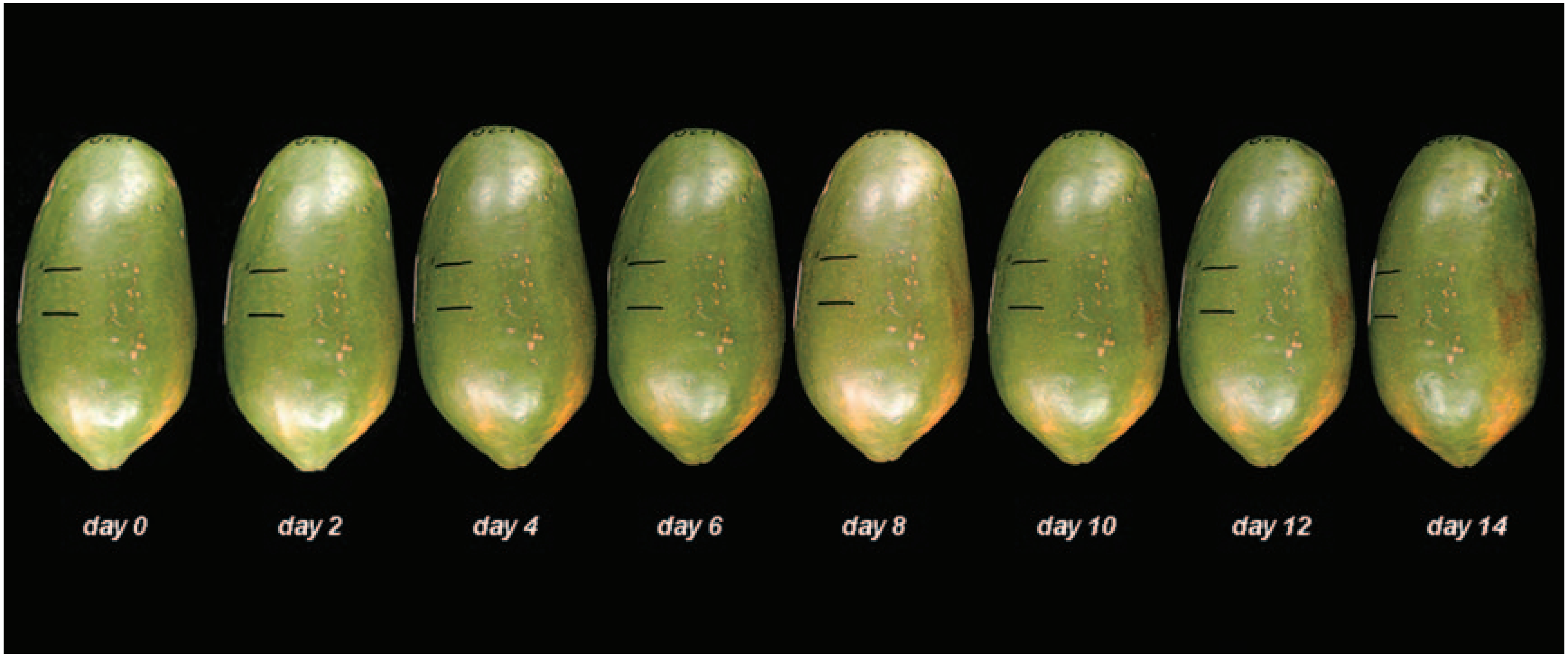
day 0
day 2
day 4
day 6
day 8
day 10
day 12
day 14

Figure 1.42. Appearance of 'Exp. 15' papaya stored for 14 days at 0°C. Fruit maintains acceptable visual quality for 12 days, but subtle skin pitting becomes evident after 4 days.

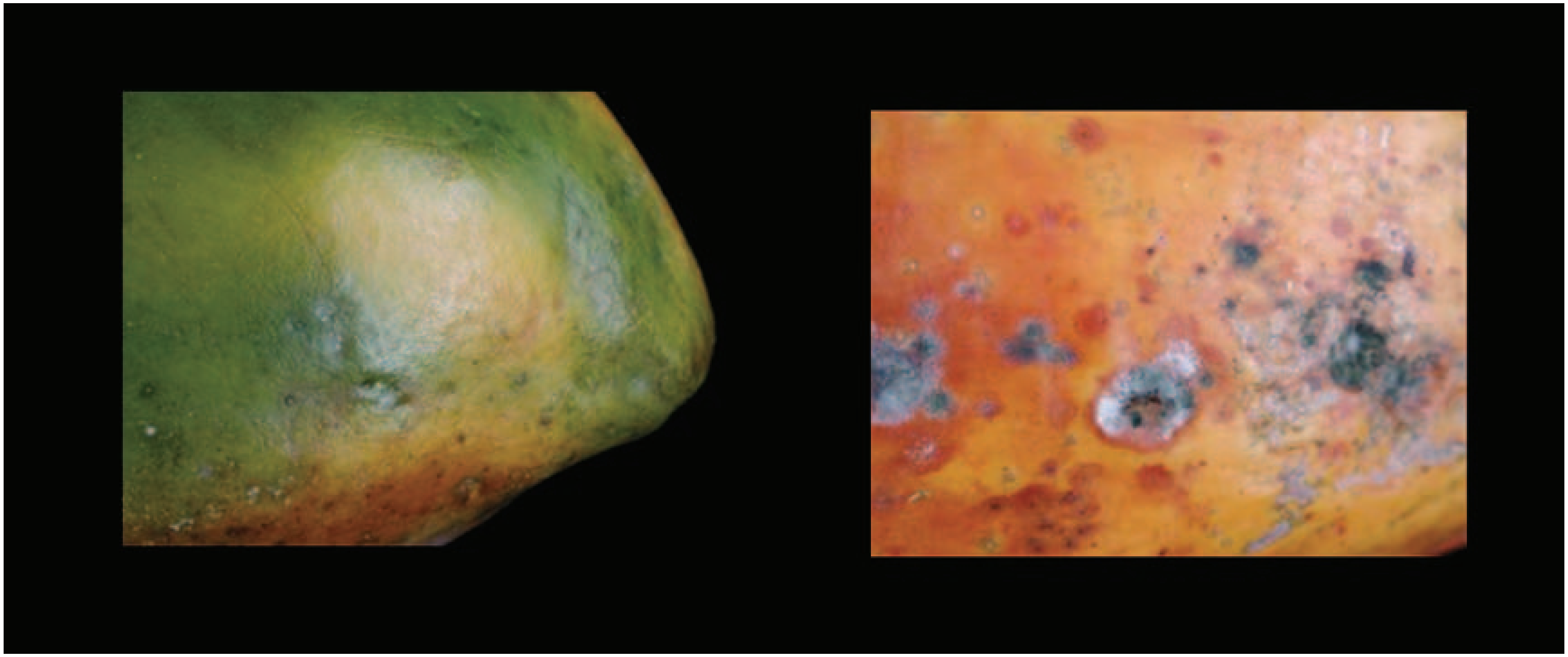

Figure 1.43. Symptoms of CI in papaya 'Exp. 15', such as shriveling of the skin and pitting after 4 days at 0°C (left), followed by decay of the pits after transfer to ambient temperature (20°C) for 2 days (right).

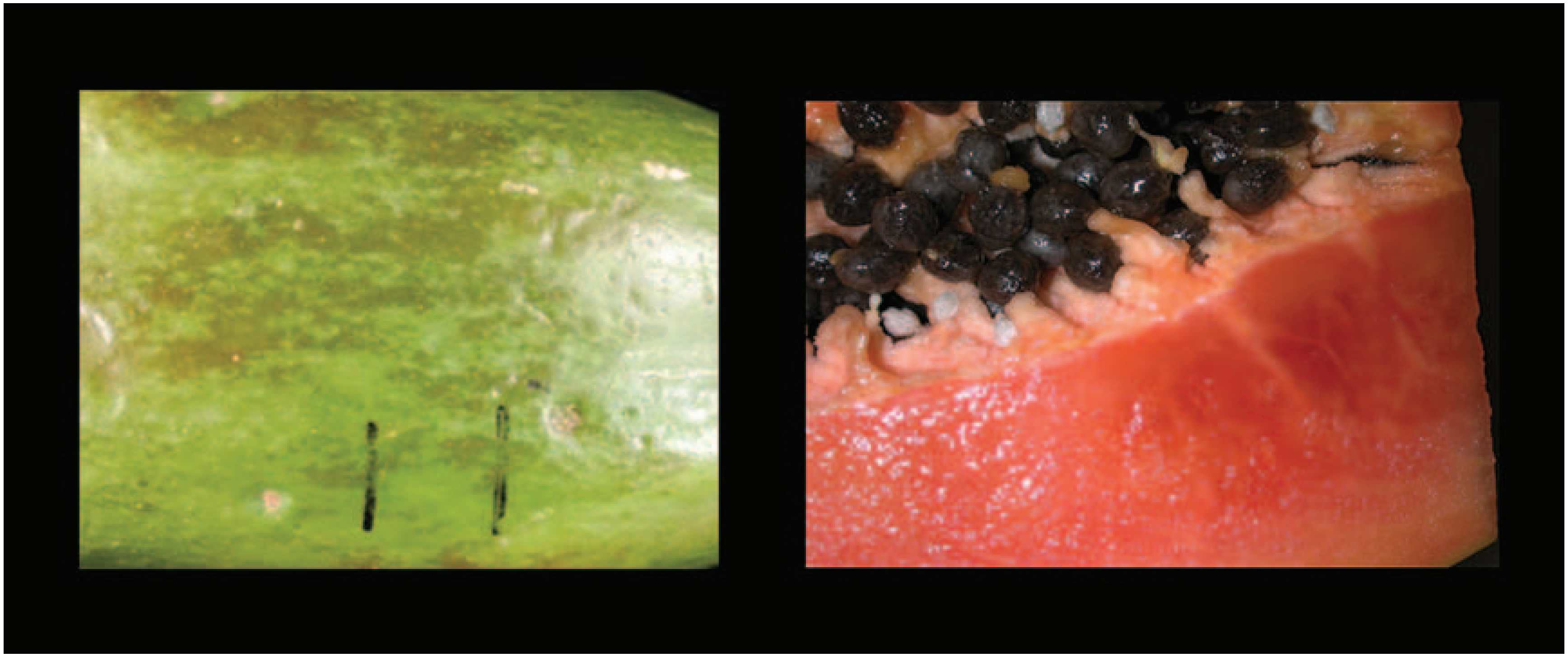

Figure 1.44. Severe symptoms of CI, such as external (left) and internal water-soaking (right), in ‘Exp. 15’ papayas stored for 12 days at 0°C after transfer to 20°C for 2 days.

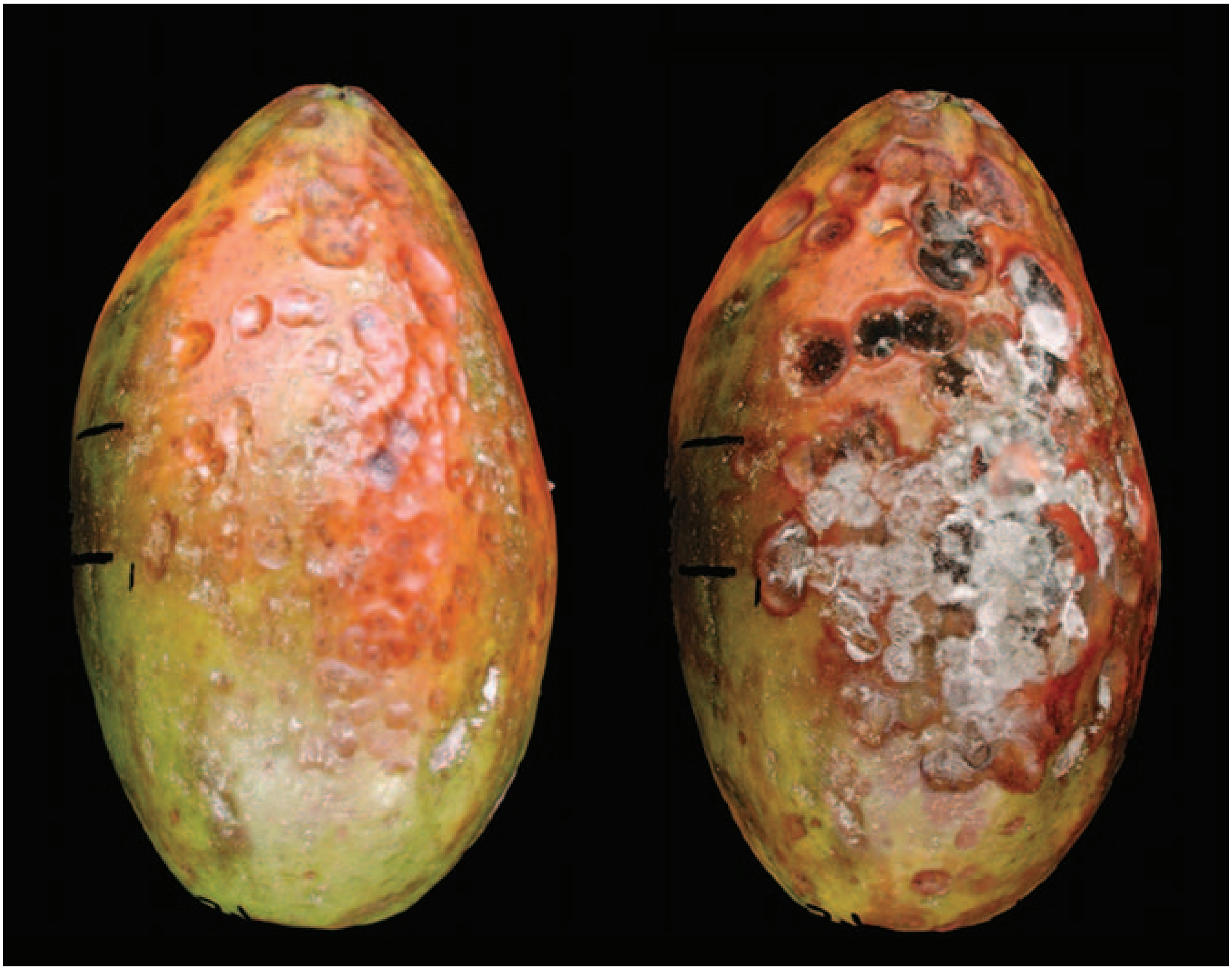

Figure 1.45. Severe pitting and decay in 'Exp. 15' papaya after storage for 14 days at 0°C (left) followed by transfer for 2 days at 20°C (right).

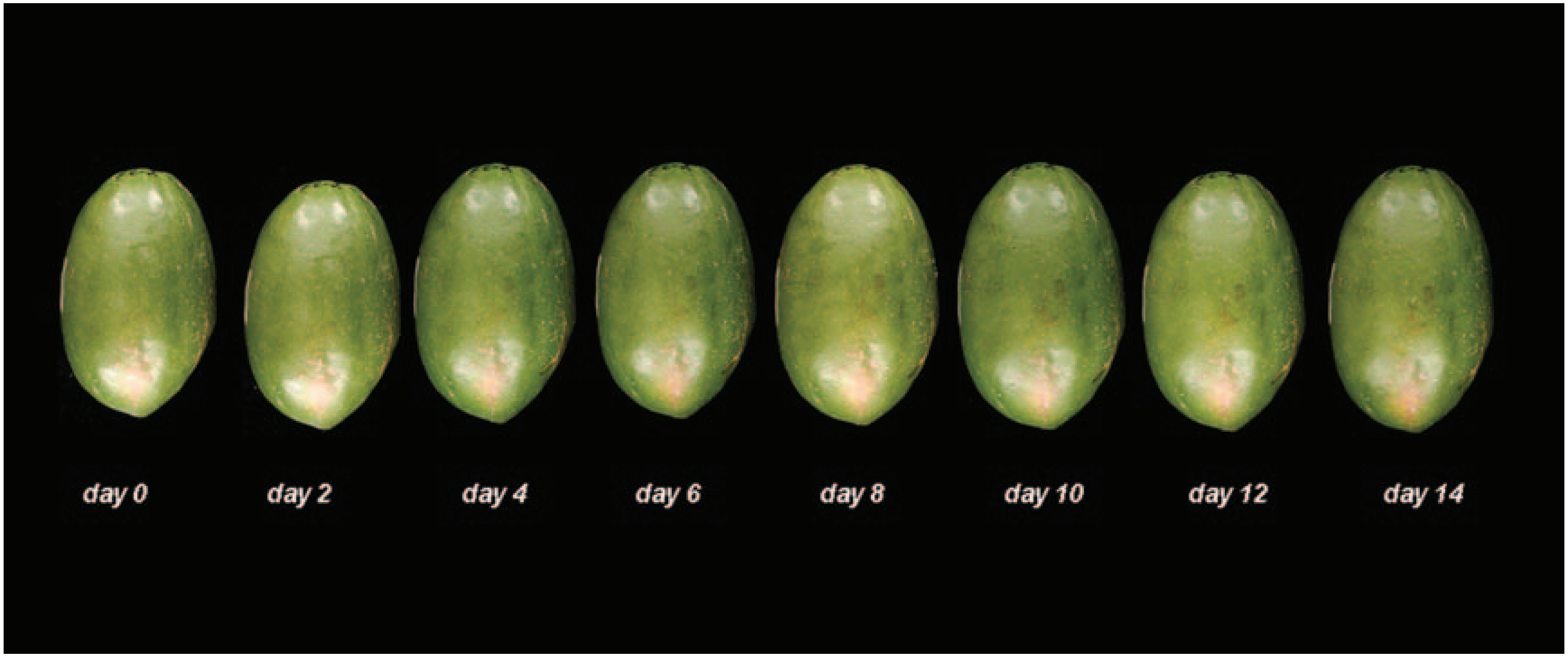
day 0
day 2
day 4
day 6
day 8
day 10
day 12
day 14

Figure 1.46. Appearance of 'Exp. 15' papaya stored for 14 days at 5°C. Fruit maintains acceptable visual quality for 6–8 days, when skin pitting becomes evident.

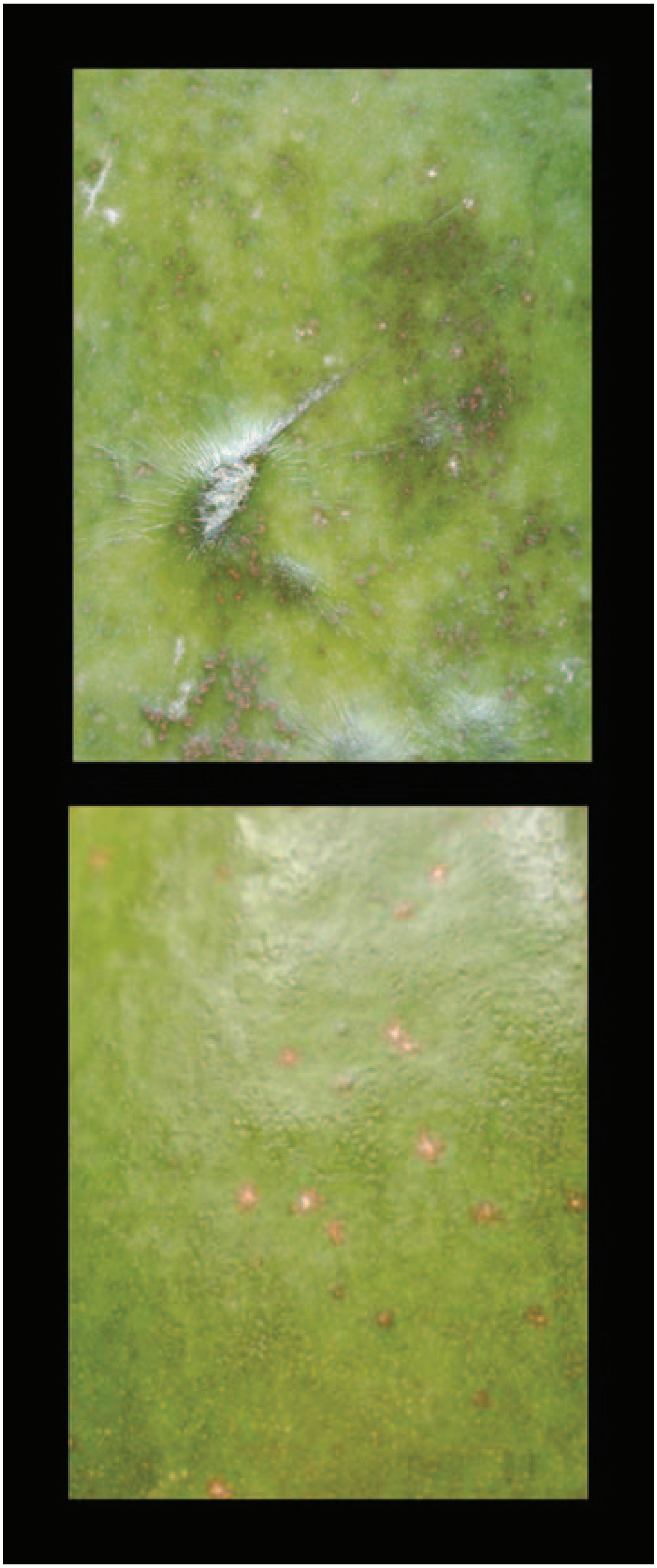

Figure 1.47. Pitting after storage of 'Exp. 15' papaya for 10 days at 5°C (left) and mycelium growth on the pits after transfer to 20°C for 2 days (right).

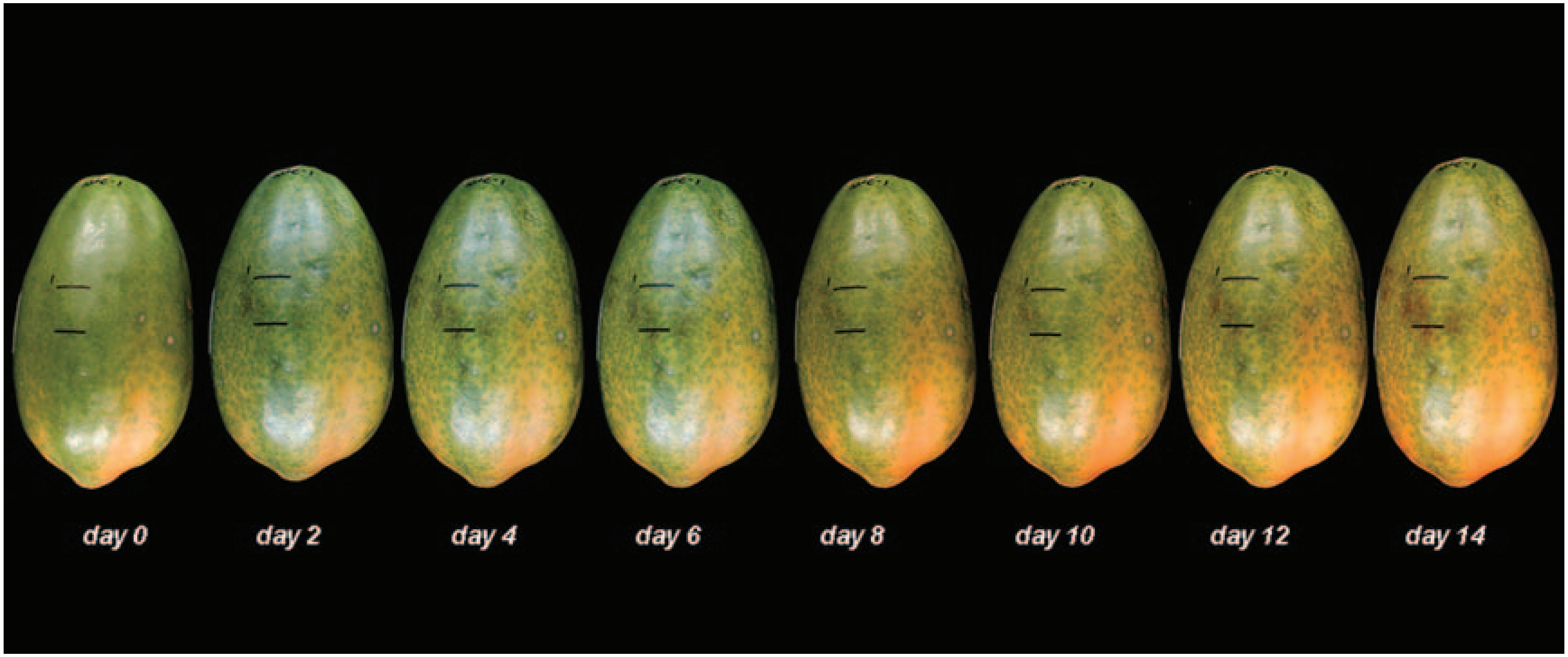
day 0
day 2
day 4
day 6
day 8
day 10
day 12
day 14

Figure 1.48. Appearance of 'Exp. 15' papaya stored for 14 days at 10°C. Fruit maintains acceptable visual quality during 8–10 days, when skin pitting becomes evident.

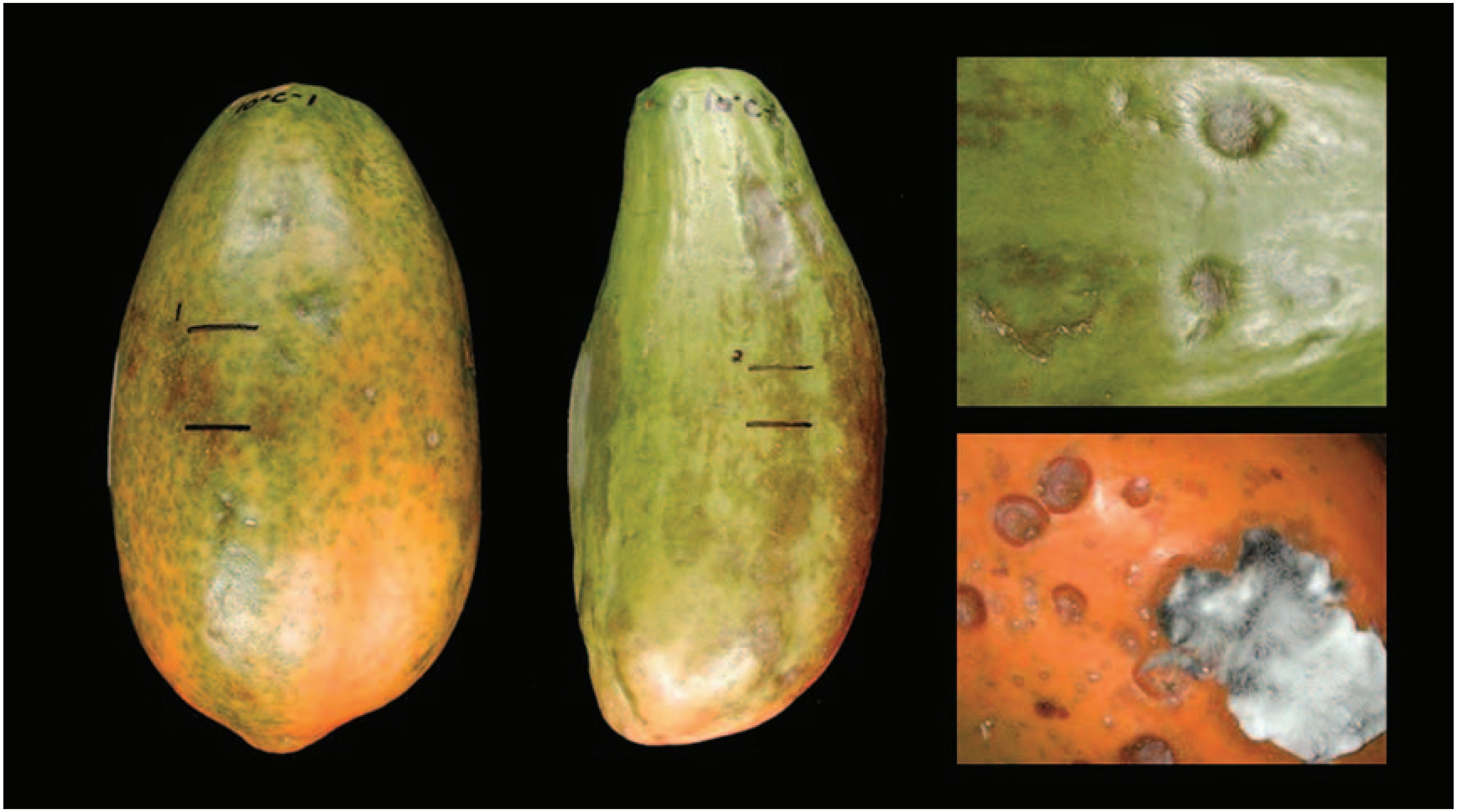

Figure 1.49. Pitting in 'Exp. 15' papaya after storage for 14 days at 10°C (left and right above), and aggravated symptoms of pitting, scalding, water-soaking, and severe decay after transfer for 2 days at 20°C (center and right below).

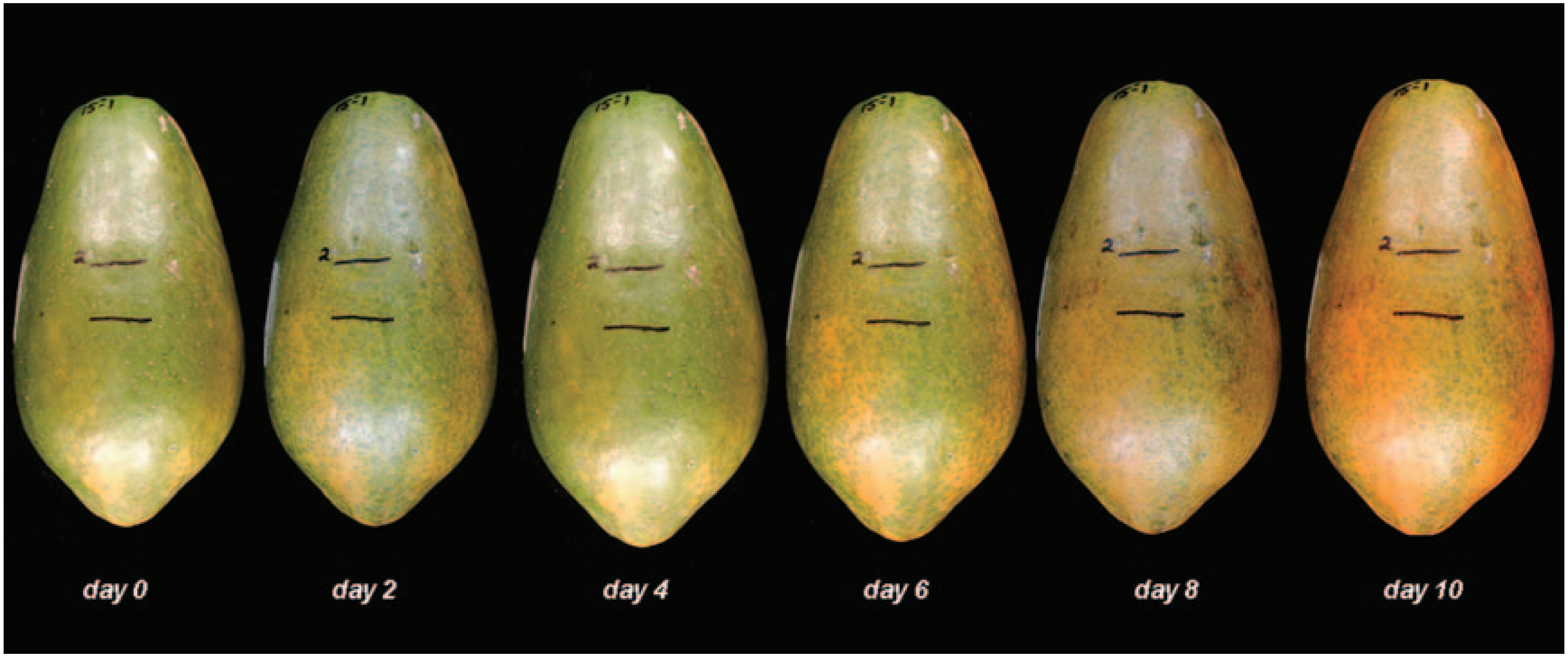
day 0
day 2
day 4
day 6
day 8
day 10

Figure 1.50. Appearance of 'Exp. 15' papaya stored for 10 days at 15°C. Fruit maintains acceptable visual quality during 8–10 days.

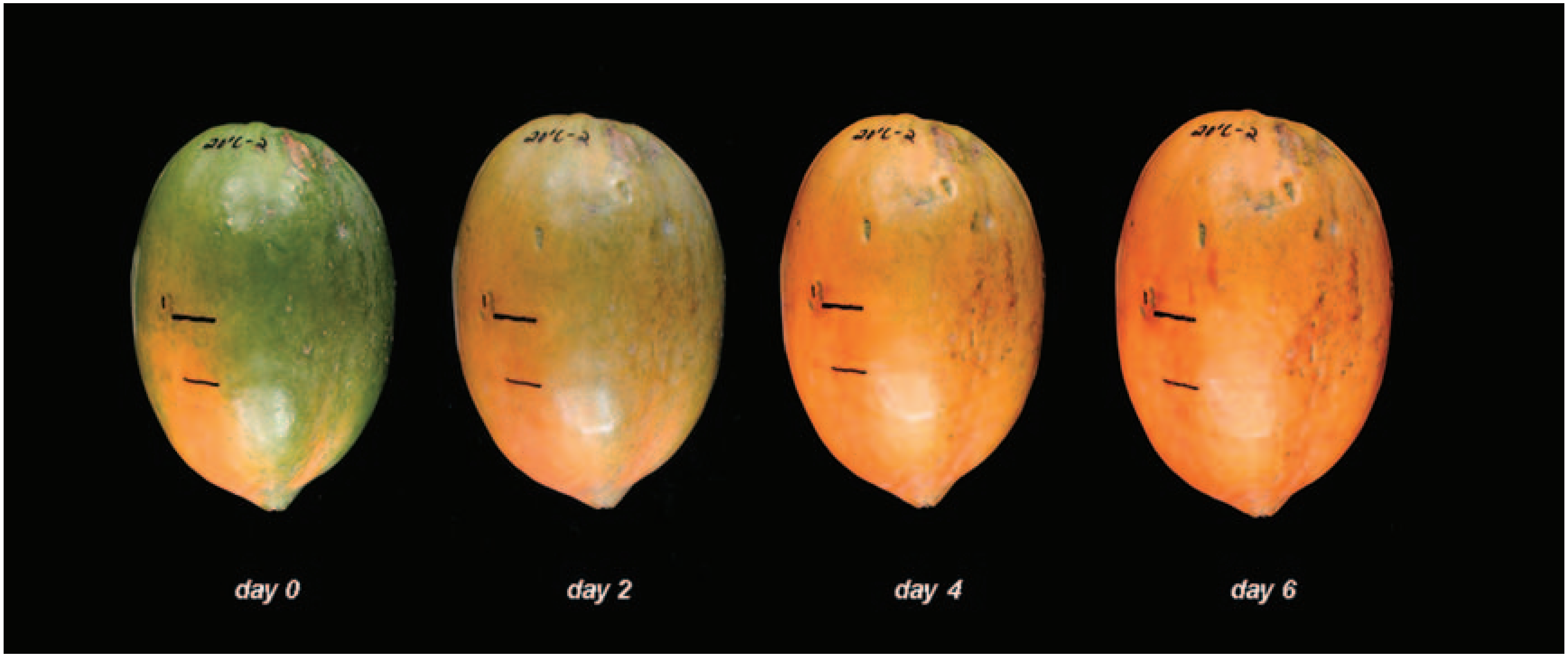
21°C-2
21°C-2
21°C-2
21°C-2
day 0
day 2
day 4
day 6

Figure 1.51. Appearance of 'Exp. 15' papaya stored for 6 days at 20°C. Fruit maintains acceptable appearance for about 4 days.

PASSION FRUIT

Scientific Name: *Passiflora edulis*
Family: Passifloraceae

Quality Characteristics

Purple and yellow passion fruits are grown throughout the tropical and subtropical regions of the world, but passion fruit has a particular commercial importance in Australia, Hawaii, South Africa, and Brazil (Knight and Sauls 2005). The yellow passion fruit is larger than the purple passion fruit and has a hard, thick yellow rind, brown seeds, and an acidic pulp with a strong aromatic flavor. The purple passion fruit has a purple skin and black seeds. The pulp from both fruits varies from yellow to orange in color. The purple passion fruit has a more pleasant flavor than the yellow, and for this reason is preferred for consuming as a fresh fruit. The yellow passion fruit is usually used for processing (Bora and Narain 1997). When full maturity is attained, the color of the fruit turns from green to yellow or purple within a few days (Knight and Sauls 2005; Shiomi et al. 1996a). When ripe, the fruit drops to the ground; it should not be picked from the vine, as the fruit has an unripe woody-like taste (Kader 2006b; Knight and Sauls 2005). Consumers seem to prefer purple passion fruit with at least 90% of the surface showing color, whereas fruit with less than 10% of the surface color is usually unacceptable for marketing (Arjona and Matta 1991). However, as soon as the ripe full-colored fruit falls it starts to lose moisture rapidly and become extremely shriveled. Although the juice and the edible portion of the fruits remain acceptable, the wrinkled appearance makes the fruit unacceptable for sale (Kader 2006b; Knight and Sauls 2005).

Size, shape, skin condition and color, acidity, and soluble solids contents are the major characteristics used to evaluate passion fruit quality. The soluble solids content varies from 10 to 18% in yellow and from 10 to 20% in purple passion fruit, whereas the acid content varies from 2.1 to 5.0% depending on the cultivar, with the yellow fruit having a more acidic flavor (Bora and Narain 1997; Kader 2006b; Paull and Chen 2004; Romero-Rodriguez et al. 1994). Compared to purple passion fruit, yellow passion fruit has the lowest percentage of pulp, higher pH, soluble solids, glucose and sucrose contents, and slightly lower fructose content (Arjona et al. 1991; Chan and Kwok 1975). As the fruit ripens, moisture content, pH, and acidity decrease, whereas soluble solids content and total sugars increase (Bora and Narain 1997; Enamorado et al. 1995; Shiomi et al. 1996a). Ascorbic acid seems to attain a maximum level at the mature-green stage, and then remains unchanged until the fruit is fully ripe (Bora and Narain 1997).

Passion fruit contains about 70–89% water, 6–23% carbohydrates, and 2–3% proteins (Homnava et al. 1990; Paul and Southgate 1985; Romero-Rodriguez et al. 1994; USDA 2006). Passion fruit juice, and, in particular, the edible seeds are considered an excellent source of dietary fiber. On average, passion fruit contains about 10–16% dietary fiber (Homnava et al. 1990; Paul and Southgate 1985; Romero-Rodriguez et al. 1994; USDA 2006), but the edible seeds may contain more than 65% dietary fiber (Chau and Huang 2004). Passion fruit is also a good source of vitamin C, containing between 20 and 30 mg of vitamin C and 1,272 IU of vitamin A per 100 g of fresh fruit, as well as other vitamins in smaller amounts (Bora and Narain 1997; Paul and Southgate 1985; Romero-Rodriguez et al. 1994).

Optimum Postharvest Handling Conditions

Passion fruit should be room or forced-air cooled to 10°C promptly after harvest to reduce loss of quality (Paull and Chen 2004). Partially ripe passion fruit may be stored between 7 and 10°C for 3–5 weeks, whereas fully ripe fruit may be stored between 5 and 7°C for 1 week (Kader 2006b; Paull and Chen 2004). Yellow passion fruit may be stored for 15 days at 10°C (Arjona et al. 1992). To avoid shriveling, the fruit may be wrapped in plastic film; otherwise it should be maintained in an environment with 90–95% relative humidity (Arjona et al. 1994; Kader 2006b; Knight and Sauls 2005; Paull and Chen 2004). If fruit is stored at temperatures of 5°C or below, CI may occur and the fruit may develop surface and internal discoloration, pitting, water-soaked areas, uneven ripening or failure to ripen, off-flavor, and increased decay incidence (Kader 2006b; Paull and Chen 2004).

Temperature Effects on Quality

Storage temperature, humidity, and length of storage have a great influence on the visual quality attributes of passion fruit. Shriveling of the skin is probably one of the most important signs of deterioration during storage, regardless of the storage temperature. In fact, external appearance of yellow passion fruit declined with storage time, regardless of the temperature when fruit was stored for 45 days at 5, 10, or 15°C. Yellow passion fruit stored at 5 or 15°C deteriorated rapidly and had a higher weight loss than fruit stored at 10°C. However, fruit stored at 10°C had the least surface shriveling and weight loss after 15 days. Therefore, shriveling increased with increasing storage length. Eighty-four, 40, and 50% of the fruit surface was shriveled after storage for 15 days at 5, 10, and 15°C, respectively (Arjona et al. 1992).

Loss of water during storage is one of the main causes of deterioration, as it results in loss of fruit weight and unacceptable appearance due to shriveling, wilting, and loss of firmness (Bora and Narain 1997). Weight loss of purple passion fruit significantly increased during storage at 25°C. After approximately 20 days, fruits harvested at the mature or fully ripe stage had lost 25% of their initial weight (Shiomi et al. 1996a). Weight loss of yellow passion fruit stored at 5, 10, or 15°C increased with storage time, regardless of the temperature. The largest amount of weight loss (62–65%) occurred at 10 and 15°C after 45 days of storage, compared to 48% weight loss in fruit stored at 5°C for the same period (Arjona et al. 1992). Wrapping passion fruit in plastic film prior to storage at 10°C for 15 or 30 days reduced weight loss and shriveling of the fruit compared to nonwrapped fruit. Weight loss in nonwrapped fruit attained 51% after 30 days of storage, whereas the wrapped fruit lost 14% of its initial weight after the same period (Arjona et al. 1994). Likewise, passion fruit wrapped in plastic film and stored at 20–25°C and 70–85% humidity was more turgid, lost less mass, and had less shriveling than nonwrapped fruit (Mota et al. 2003).

Passion fruit composition and nutritional value are greatly affected by storage time and temperature. For example, although soluble solids content of yellow passion fruit stored at 5°C did not change significantly during storage, soluble solids content of fruit stored at 10 or 15°C for 45 days significantly decreased during storage from an initial value of 15.3% to 13.0% and 4.6%, respectively. Sucrose, fructose, and glucose contents decreased dramatically after storage for 45 days at 15°C, whereas less dramatic changes were observed in passion fruit stored at 5 or 10°C. Overall, soluble sugars were maintained at a higher level when the fruit was stored at 5 and 10°C than at 15°C (Arjona et al. 1992). Sucrose content of purple passion fruit decreased and fructose and glucose contents increased during storage at 10°C (Arjona and Matta 1991). Soluble solids content of mature-green and fully ripe purple passion fruit stored at 25°C decreased from about 17% at harvest to about 12% after 20 days of storage. Likewise, acidity of full ripe fruit decreased from about 3.5% at the time of harvest to about 1.5% after 15 days of storage at 25°C (Shiomi et al. 1996a). Sucrose content of passion fruit harvested at the turning stage decreased during storage at 25°C, whereas a gradual increase in glucose and fructose was observed after 15 days of storage. Citric and malic acids slightly increased from the time of harvest to day 5 after harvest, and decreased afterward (Shiomi et al. 1996b).

Ascorbic acid content of passion fruit stored at 4°C decreased from an initial value of 64.78–39.36 mg per 100 g fruit fresh weight, after only 1 week of storage. This represented a 39.2% loss in the initial ascorbic acid content of the fruit (Vinci et al. 1995). Volatile compounds, responsible for the floral mixed fruit character of the juice and the sweet aroma of the fruit, also decreased rapidly when passion fruit was stored at 29°C. After 3 days this fruit had lost its fresh characteristic aroma (Narain and Bora 1992).

Time and Temperature Effects on the Visual Quality of 'Possum Purple' Passion Fruit

'Possum Purple' red passion fruit shown in Figures 1.52–1.58 was harvested full ripe, from a commercial operation in Homestead, Florida, during the spring season (i.e., April–May). Promptly after harvest, fresh passion fruit was stored at five different temperatures (0.5 ± 0.3°C, 5.0 ± 0.2°C, 9.4 ± 0.4°C, 14.40 ± 0.4°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Shriveling, darkening of color, and development of decay are the most important visual quality changes observed in 'Possum Purple' passion fruit stored at different temperatures.

'Possum Purple' passion fruit stored at 0°C maintains acceptable visual quality during 12–16 days of storage (Figure 1.52). However, after 16 days, shriveling and browning of the peel become evident and aggravate as storage progresses. After 32 days the whole fruit appears severely shriveled and the peel develops objectionable reddish-brown coloration. When fruits stored for 4 days at 0°C are transferred to 20°C for 1 additional day, passion fruit develops severe symptoms of CI such as brown discoloration of the skin, uneven ripening, shriveling, pitting, and water-soaked appearance (Figure 1.53). The symptoms aggravate significantly with increased exposure to 0°C, and the peel of the fruit becomes completely dark-brown, shriveled, and with some decayed spots after 32 days of storage. At this time, the color of flesh appears less bright greenish-orange and less juicy than at the time of harvest, and releases objectionable odors, whereas the taste is very disagreeable.

Peel shriveling develops much slower in 'Possum Purple' passion fruit stored at 5°C compared to fruit stored at 0°C. Fruit stored at 5°C maintains acceptable visual quality during 32 days, but afterward, shriveling increases and becomes objectionable after 40 days of storage (Figure 1.54). However, after transfer to 20°C for 1 additional day, symptoms of CI become evident in fruit stored for 6 days at 5°C (Figure 1.55). Therefore, passion fruit held at 5°C for 6 days develops an objectionable dark greenish-red brown color upon transfer to warmer temperature. The symptoms aggravate with increasing the storage period, and after 18 days decay develops in some areas of the fruit. After 32 days the fruit appears very shriveled and decayed. At this time, there is a marked reduction in peel thickness, the flesh color appears less bright greenish-orange and is less juicy than at harvest, and the flesh tastes bad and releases objectionable odors.

‘Possum Purple’ passion fruit stored at 10, 15, or 20°C did not develop any CI symptoms, but at these temperatures shriveling develops much faster than at lower temperatures. Therefore, at 10°C, the first signs of peel shriveling are noticeable after 12 days, and increase as storage time progresses until becoming objectionable after 30 days (Figure 1.56). After 50 days at this temperature, decay develops on sunken areas of the fruit; discoloration of the peel is also perceptible, whereas the flesh color appears less bright greenish-orange and is less juicy than at the time of harvest.

First signs of peel shriveling develop on ‘Possum Purple’ passion fruit after 6 days at 15°C, increase as storage progresses, and become objectionable after 12 days (Figure 1.57). After 50 days at this temperature, decay develops on sunken areas of the fruit; discoloration of the peel is also perceptible, whereas the color of flesh appears less bright greenish-orange and is less juicy than at the time of harvest. At this time, there is also a marked reduction in the thickness of the peel.

Visual quality changes are very fast in ‘Possum Purple’ passion fruit stored at 20°C. First evidence of shriveling develops after 4 days, but the fruit maintains acceptable visual quality during 6 days (Figure 1.58). Shriveling increases rapidly afterward and becomes objectionable after 12 days of storage. After 16 days, the fruit color changes and some areas of the peel develop a reddish-brown discoloration. Decay develops on the stem-end of fruit after 20 days, creating an area of dark brown discoloration, and after 24 days the internal part of the fruit is also affected by decay, showing mycelium growth. At this time, there is a marked reduction in the thickness of the peel, and the color of flesh appears less bright greenish-orange and less juicy than at the time of harvest and releases objectionable odors.

Overall, visual quality of ‘Possum Purple’ passion fruit is better maintained when fruit is stored at 10°C (30 days), compared to storage at higher or lower temperatures. Passion fruit stored at 0°C retains acceptable visual quality during 4 days, whereas visual quality of fruit stored at 15°C is still acceptable after 12 days. Fruit stored at 5 and 20°C maintains acceptable visual quality during 6 days.

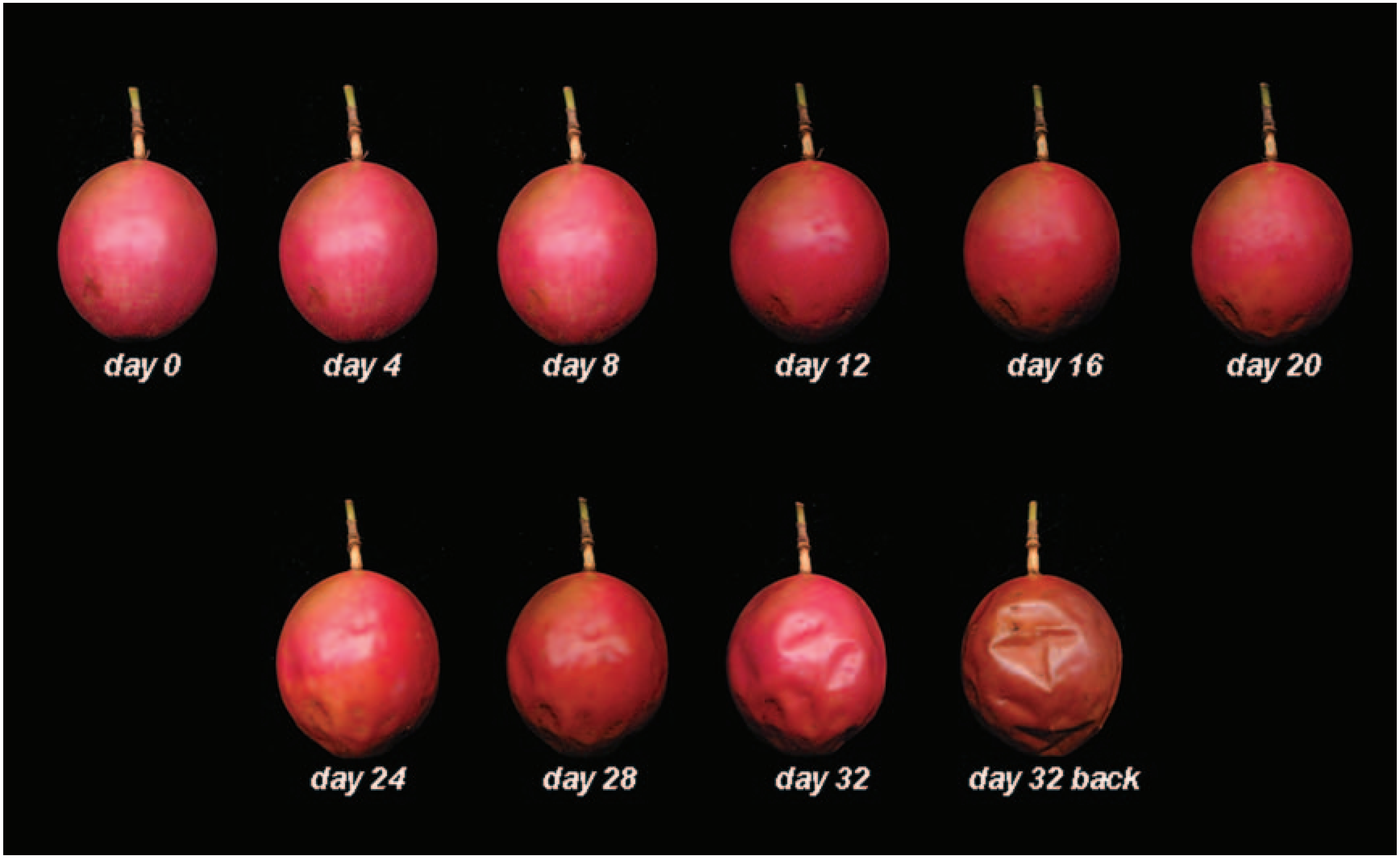
day 0
day 4
day 8
day 12
day 16
day 20
day 24
day 28
day 32
day 32 back

Figure 1.52. Appearance of ‘Possum Purple’ passion fruit stored for 32 days at 0°C. The fruit maintains acceptable visual quality during 12 or 16 days of storage. After 32 days, shriveling and browning of the skin become objectionable.

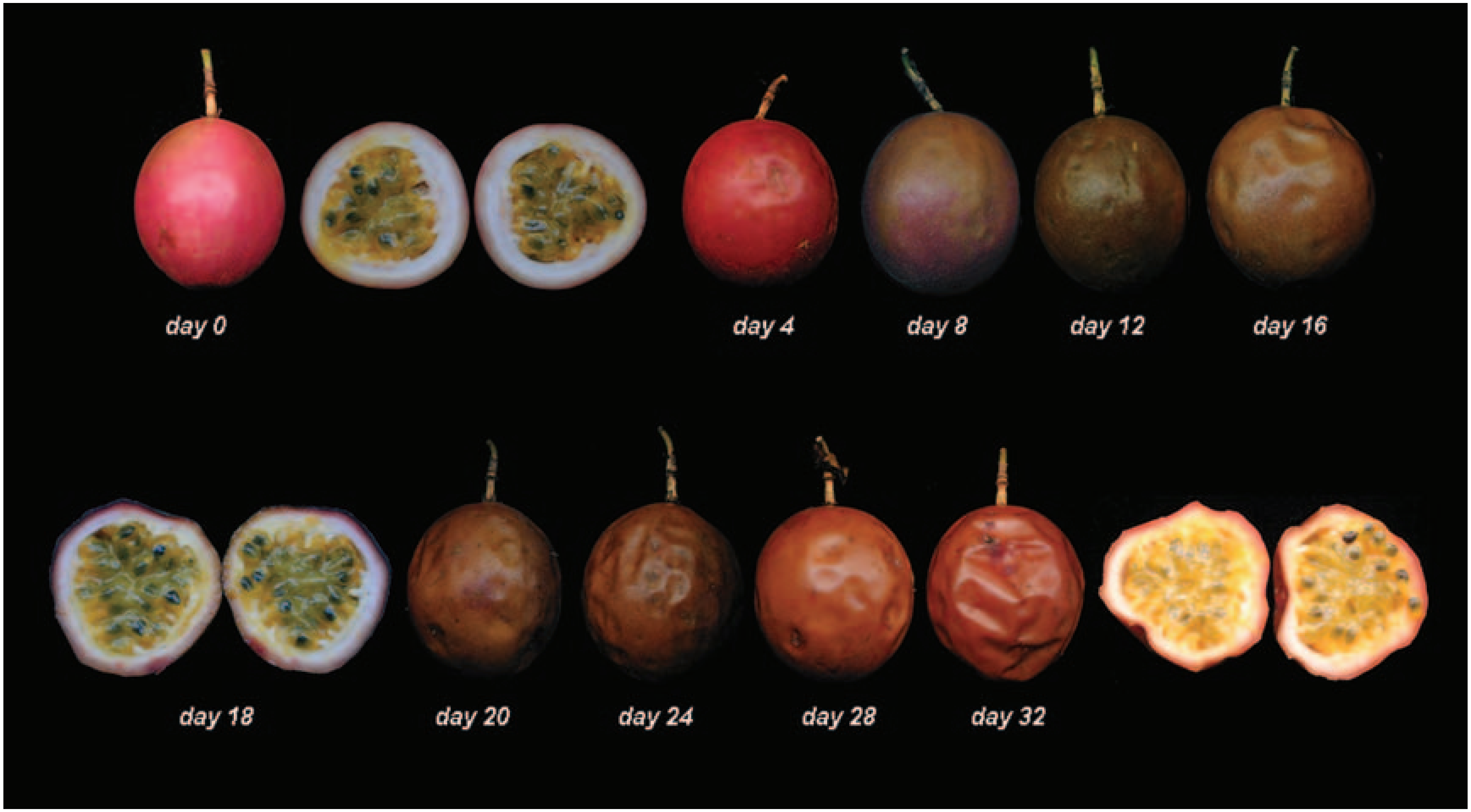
day 0
day 4
day 8
day 12
day 16
day 18
day 20
day 24
day 28
day 32

Figure 1.53. Chilling injury in 'Possum Purple' passion fruit after storage at 0°C plus transfer for 1 day at 20°C. After 4 days the fruit develops objectionable brown color.

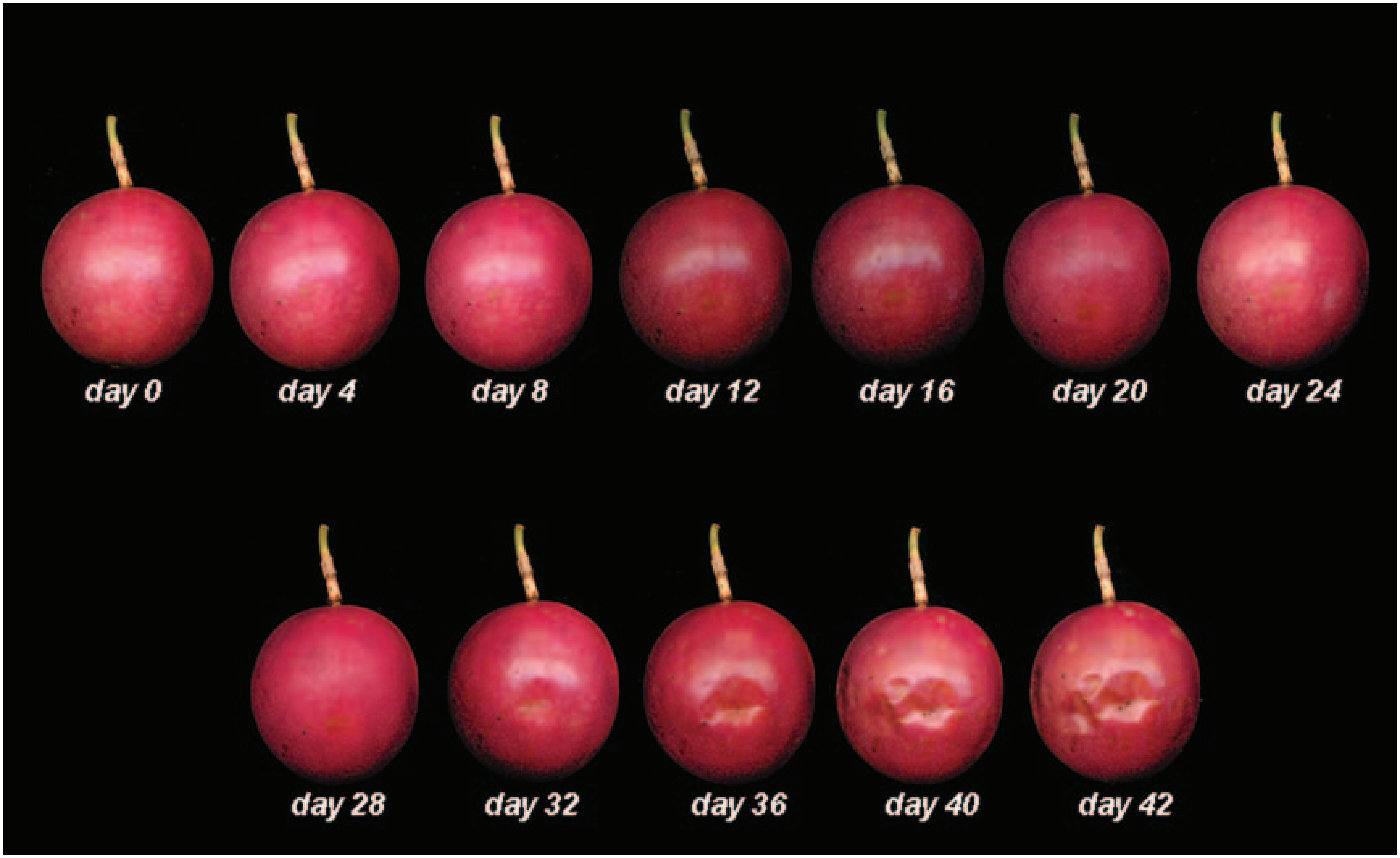
day 0
day 4
day 8
day 12
day 16
day 20
day 24
day 28
day 32
day 36
day 40
day 42

Figure 1.54. Appearance of 'Possum Purple' passion fruit stored for 42 days at 5°C. Fruit maintains acceptable visual quality during 32 days. After 42 days, fruit shriveling is evident.

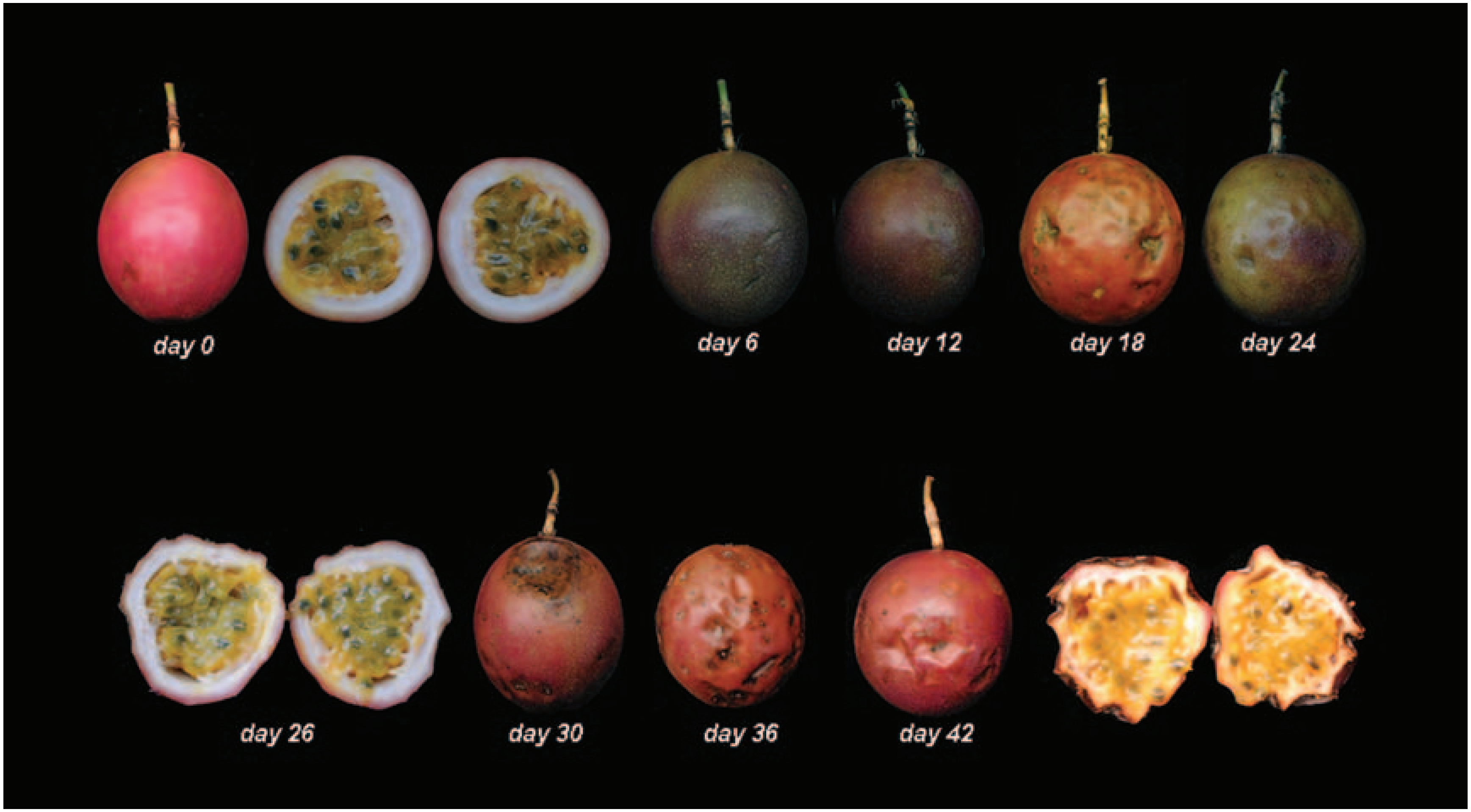
day 0
day 6
day 12
day 18
day 24
day 26
day 30
day 36
day 42

Figure 1.55. Chilling injury in 'Possum Purple' passion fruit after storage at 5°C plus transfer for 1 day at 20°C. Fruit develops a dark brownish color after 6 days, and after 18 days decay develops on the fruit surface.

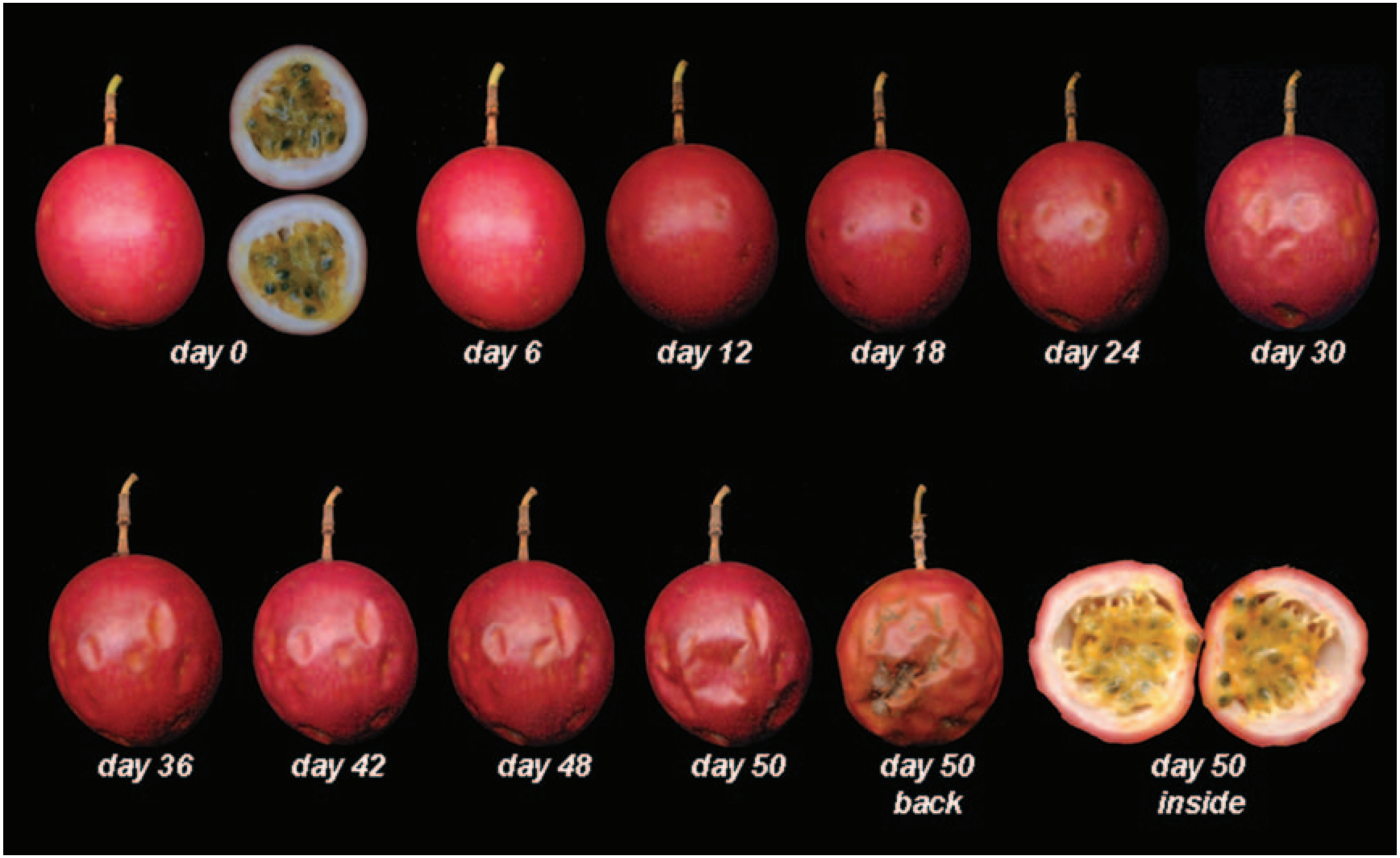
day 0
day 6
day 12
day 18
day 24
day 30
day 36
day 42
day 48
day 50
day 50 back
day 50 inside

Figure 1.56. Appearance of 'Possum Purple' passion fruit stored for 50 days at 10°C. Fruit maintains acceptable visual quality during 30 days. After 50 days, decay develops on the fruit surface.

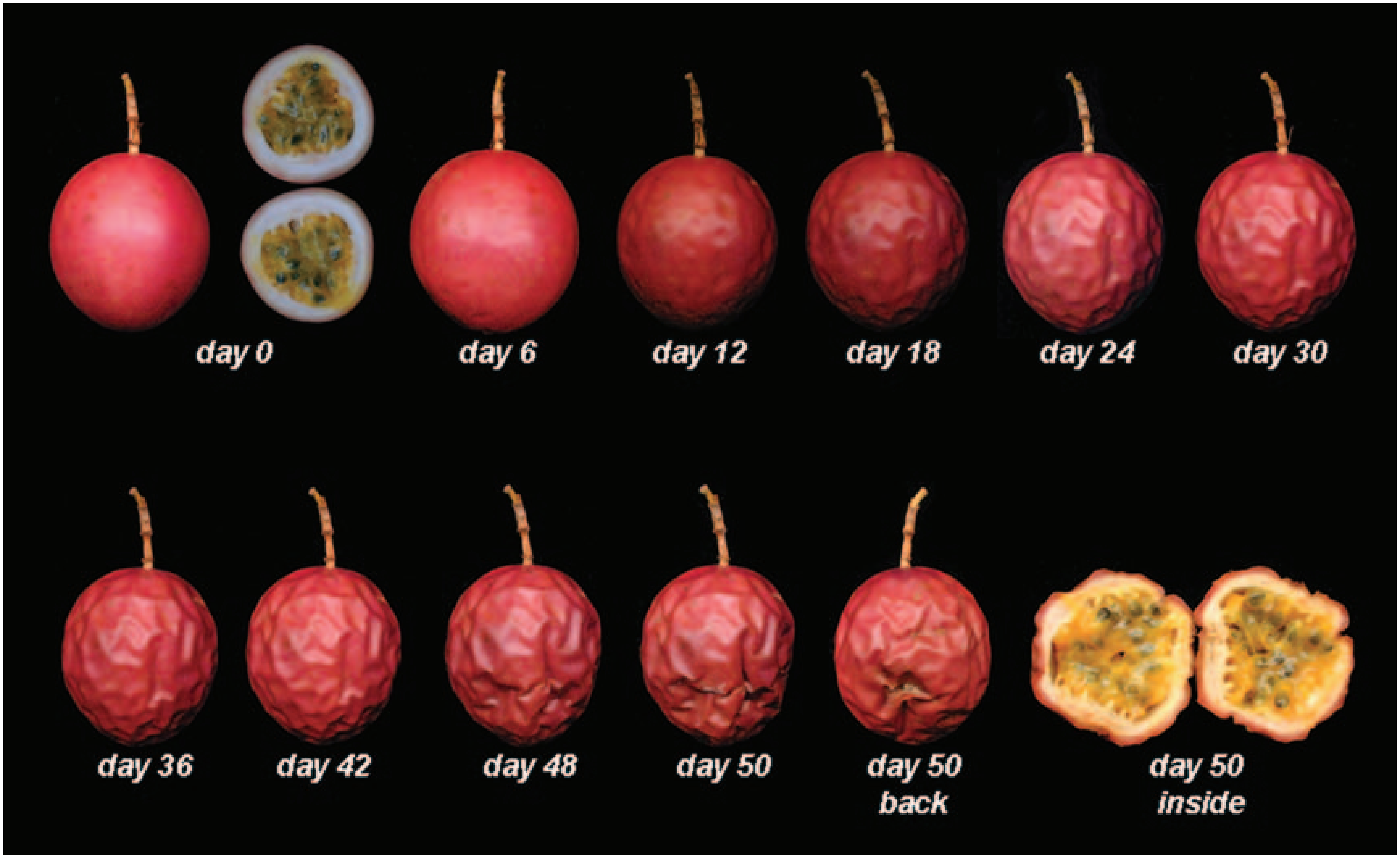
day 0
day 6
day 12
day 18
day 24
day 30
day 36
day 42
day 48
day 50
day 50 back
day 50 inside

Figure 1.57. Appearance of 'Possum Purple' passion fruit stored for 50 days at 15°C. Fruit maintains acceptable visual quality during 12 days. After 50 days, decay develops on the fruit surface.

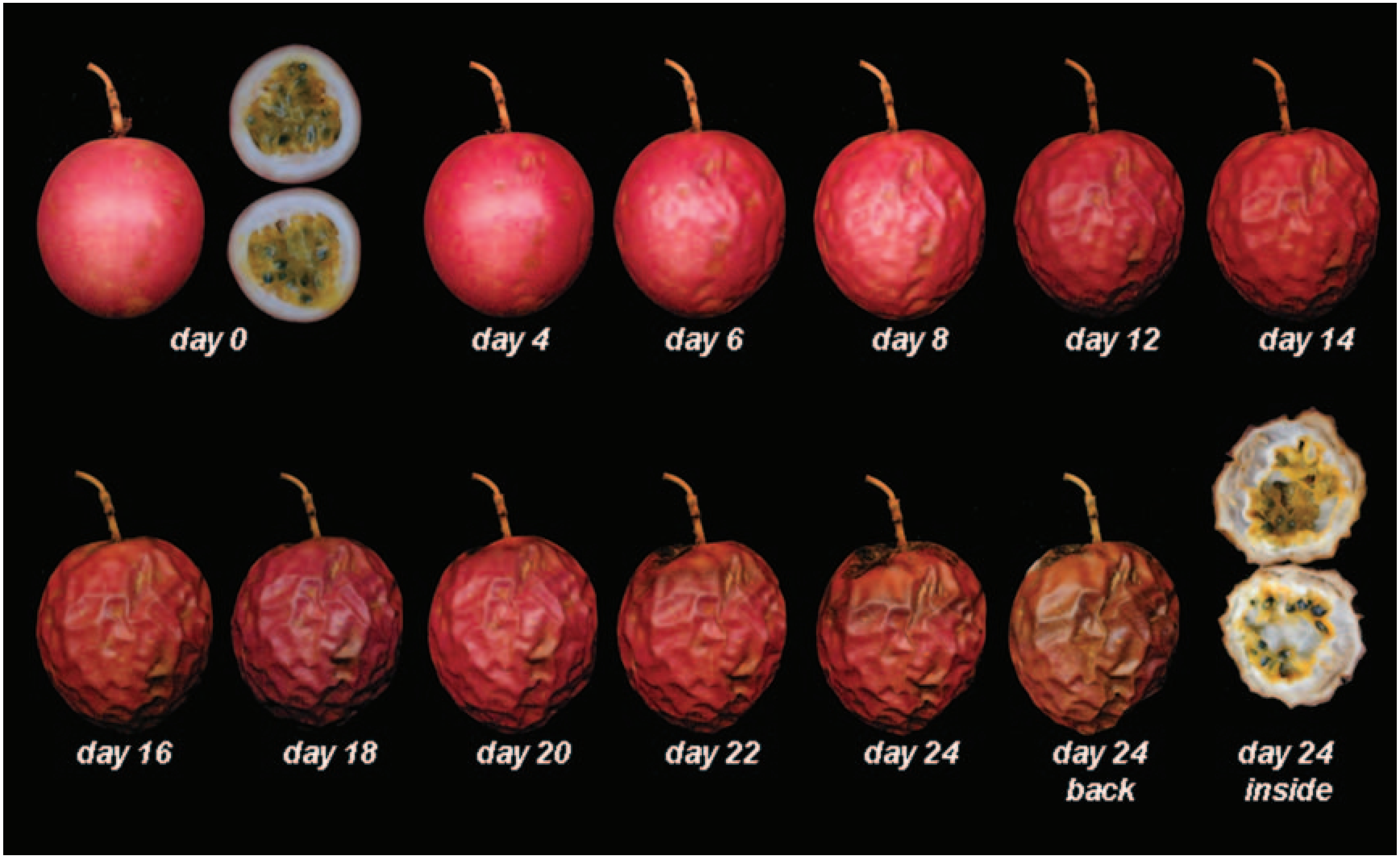
day 0
day 4
day 6
day 8
day 12
day 14
day 16
day 18
day 20
day 22
day 24
day 24 back
day 24 inside

Figure 1.58. Appearance of 'Possum Purple' passion fruit stored for 24 days at 20°C. Fruit maintains acceptable visual quality during 6 days. Decay develops on the fruit surface after 20 days, and after 24 days the internal part of the fruit is also affected by decay.

CARAMBOLA

Scientific Name: *Averrhoa carambola* L.
Family: Oxalidaceae

Quality Characteristics

Carambola, also known as star fruit, is cultivated in many tropical and subtropical areas of the world. The fruit is a fleshy five-celled berry with a waxy surface and star-shaped in cross section. The skin of the fruit is thin and smooth, with a waxy cuticle, and light to dark yellow when the fruit is ripe. The flesh is light to dark yellow, translucent, crisp, very juicy, and not fibrous. Carambola cultivars vary in their sweetness and acidity, but good quality cultivars have an agreeable sweet-acid flavor (Crane 1994; Scheerens 1994). Sweet cultivars (pH of 3.8–4.1) include 'Arkin' and tart cultivars (pH of 2.2–2.6) include 'Golden Star.' Depending on the cultivar, the soluble solids content of the fruit may vary between 4 and 11%. 'Arkin' carambola, the major cultivar grown in Florida, is considered a sweet fruit, with low acidity, firm, and with a pleasant flavor. The external color is of a deep shiny yellow, and the flesh is yellow, crisp, juicy, sweet, and with a mild aroma of tea roses (Campbell 1997; Crane et al. 1998; Knight and Crane 2002). The aroma of Malaysian carambolas was described as peach-apricot-plum–like (MacLeod and Ames 1990). In general, a good quality carambola should be firm and glossy, with no brown discoloration on the rib skin, and should have a crispy and juicy flesh (Kader 2006a; Paull and Chen 2004). Peel discoloration, pitting, stem-end breakdown, and fin browning are the major visible indicators of quality loss and negatively affect consumer acceptance (Miller and McDonald 1997).

Depending on the time of harvest, soluble solids content of 'Arkin' carambolas may vary between 4 and 8%, with acidity of 0.212% (Crane et al. 1998; Knight and Crane 2002). During ripening of Malaysian carambolas, total soluble solids content, pH, sugars, and ascorbic acid contents increased. At the full orange-yellow stage, the chemical composition of the fresh fruit was 11.2% total soluble sugars, pH of 4.5, 0.25% acidity, 8% total sugars, and 40.2 mg ascorbic acid per 100 g fresh weight (Ali and Jaafar 1992; Oslund and Davenport 1983). Likewise, sugar content increases during ripening of 'Arkin' carambolas, and, at color break, fructose was the predominant sugar (15 mg/g), followed by glucose (13 mg/g) and sucrose (4 mg/g). The major acids in 'Arkin' carambolas harvested at the color break were oxalic (1.5 mg/g) and malic (1.0 mg/g) (Campbell et al. 1987). Compared to 'Arkin,' 'Golden Star' carambolas have a much higher content of oxalic acid (5.8 mg/g) and lower malic acid content (0.4 mg/g), which contributes to the tart taste of the fruit (Campbell and Koch 1989). Tasty fruit were reported to have a total soluble solids content-to-acidity ratio of 14:1, with an optimum ratio of 16:6 (O'Hare 1993).

Simultaneously with the increase in soluble solids and sugar contents and decrease in acidity, the color of carambolas changes from green to yellow as fruit ripens, whereas firmness of the fruit decreases. Depending on the cultivar, the color of the peel may vary from a pale yellow to yellow to orange, and the flesh from a white-yellow to a yellow-orange (Crane et al. 1998). To ensure a good eating quality, carambolas should be harvested when fully yellow. However, the fruit ribbed structure is very delicate when ripe and is easily injured by handling, reducing its commercial potential. Because less ripe carambolas have a shorter shelf life and deteriorate faster during storage than riper carambolas, fruit should be harvested at the slight-yellow stage (i.e., 3–25% surface area showing yellow) instead of at the mature-green stage (Miller and McDonald 1997; Miller et al. 1996; Yon and Jaafar 1994). Although the firmness of carambola fruit tends to decrease during ripening (Chin et al. 1999; Mitcham and McDonald 1991), the ribs of 'Arkin' carambolas are thicker than most cultivars, which makes the fruit more resistant to bruising during handling (Knight and Crane 2002).

Carambolas contain on average 91% water, 7% carbohydrates, 1.0% proteins, and 1.3–2.8% fiber (Mahattanatawee et al. 2006; USDA 2006). Carambola is a relatively good source of vitamin C, and the fruit may contain between 4 and 34 mg of vitamin C per 100 g of fresh fruit, and other vitamins in smaller amounts (Leong and Shui 2002; Lim et al. 2007; Luximon-Ramma et al. 2003; Mahattanatawee et al. 2006; USDA 2006). Carotenoids are the main pigments responsible for the orange-yellow color of carambolas. The total carotenoid content of 'Golden Star' changes from 15 μg/g in unripe fruit to 22 μg/g in ripe fruit, with β-carotene comprising 0.8 and 0.6% of the total carotenoids in unripe and ripe fruit, respectively (Gross et al. 1983). Because of the generous total phenolic content (approximately 131.0–220.8 mg per 100 g fresh fruit), carambola is also considered to have a high antioxidant capacity when compared to other tropical fruits (Lim et al. 2007; Luximon-Ramma et al. 2003; Mahattanatawee et al. 2006).

Optimum Postharvest Handling Conditions

Carambolas should be pre-cooled to 4–10°C using forced-air or room-cooling promptly after harvest, to reduce loss of moisture, firmness, and glossiness (Campbell 1994; Miller and McDonald 2000; Osman and Mustaffa 1994; Paull and Chen 2004). Subsequently, and depending on the cultivar and growing area, carambolas may be stored at between 5 and 10°C. Temperatures lower than 5°C may result in CI. The intensity of CI symptoms varies depending on the cultivar, ripeness stage, and temperature and duration of storage. Because lower humidity levels may result in more severe rib-browning symptoms, humidity should be maintained between 90 and 95% during storage (Kader 2006a). If kept at 20°C and 60% relative humidity the storage life of the fruit may be as short as 3–4 days due to the development of rib-edge browning (Paull and Chen 2004). In addition, fruit to be cold-stored should not be treated with ethylene owing to enhanced decay development and stem-end browning, increased fruit softening, and decreased acceptability of flavor and texture (Miller and McDonald 1997; Miller et al. 1996).

Temperature Effects on Quality

Even when harvested green or at color break (i.e., with traces of yellow color), carambolas may change color during storage from green to yellow. However, color will change faster when the fruit is exposed to high (i.e., 20°C) temperatures. For example, ‘Golden Star’ and ‘Arkin’ carambolas harvested at the color-break stage were less green after 44 days of storage at 5 or 10°C, but carambolas kept at 5°C did not become as yellow as the fruit stored at 10°C (Campbell et al. 1987; Campbell et al. 1989). Likewise, Malaysian carambolas stored at 5°C developed color much more slowly during storage than fruit stored at 10, 15, or 20°C. Rapid color changes occurred when fruit was stored at 15 or 20°C, and after 2 weeks the fruit was more orange than yellow (Yon and Jaafar 1994).

Depending on the maturity at harvest and growing area, carambolas may develop CI when stored at temperatures lower than 5°C. In fact, CI was reported in carambolas stored for 2 weeks at 0°C or for 6 weeks at 5°C followed by 2 days at 20°C (Kader 2006a). CI symptoms are characterized by surface pitting, rib-edge browning, dark-brown patches on the skin, shriveled and darkened ribs, and failure to color upon transfer to 20°C. The pit size may vary and may appear as small (less than 1 mm), dark skin depressions or large (1–2 mm), deep, and dark brown (O’Hare 1993, Kader 2006a). ‘Arkin’ carambolas stored for 15 days at 1°C, followed by storage for 7 days at 5°C plus 3 days at 15°C, showed increased peel bronzing, stem-end breakdown, and fin browning compared to fruit stored continuously at 5°C for 28 days followed by a 3-day period at 15°C (Miller and McDonald 1997; Miller et al. 1991, 1993). Cold treatments used to reduce the incidence of Caribbean fruit flies such as cold-water dips or cold air may result in CI and loss of quality during storage of carambolas. For example, carambolas cooled in ice water for 10 minutes until the core had attained 10°C showed increased severity of pitting, bronzing, and weight loss compared with cooling with refrigerated air at 10°C (Miller and McDonald 2000). Plastic film may be used to alleviate bronzing, reduce weight loss, and maintain the quality of carambolas exposed to cold treatment (15 days at 1°C) prior to storage at 5°C (Miller et al. 1991, 1993).

‘Arkin’ carambolas stored for 30 days at 15°C showed acute fungal growth, whereas some fruit of ‘Golden Star’ carambolas remained slightly acceptable. After 30 days of storage at 20°C, ‘Arkin’ and ‘Golden Star’ carambolas showed serious decay (Campbell et al. 1987, 1989). Decay was reported to develop faster in less mature carambolas than in riper fruit. In fruit harvested mature-green, disease developed after storage for 4 weeks at 5 or 10°C, whereas in riper fruit, disease developed after 6 weeks. At 15 and 20°C all the fruits showed decay after 2 weeks of storage. Therefore, fruit stored at 15 or 20°C could be stored for only 1 week before the decay became unacceptable. Quality of carambolas deteriorated very quickly when fruits were held at 28°C after storage for 2–4 weeks at 5 and 10°C. Within 3–5 days at these temperatures the fruits were attacked by disease (Yon and Jaafar 1994).

Firmness of carambola fruit decreases during storage, but the rate of softening is slower at 5°C compared to when fruit is stored at 10, 15, or 20°C (Yon and Jaafar 1994). Likewise, ‘Arkin’ and ‘Golden Star’ carambolas stored at 10°C were considered more turgid than those stored at 15 or 20°C for a period of 30 days, and fruit stored at 5°C was firmer than that stored at 10°C (Campbell et al. 1987, 1989).

Weight loss of ‘Arkin’ and ‘Golden Star’ carambolas was greater in fruit stored at 10°C (5.3–6.7%) than at 5°C (4.2–4.4%). After transferring the fruit from 10 and 5°C to 20°C for 6 days, weight loss attained more than 10% and 20%, respectively (Campbell et al. 1987, 1989). Likewise, weight loss of ‘Arkin’ and ‘Fwang Tung’ carambolas was significantly lower at 7.5°C than at 10 or 21°C. Carambolas lost approximately 30–35% of their weight between weeks 1 and 2 when stored at 21°C (Kenney and Hull 1986).

Heat treatments used to reduce the incidence of Caribbean fruit flies such as hot-water dips or hot air may result in loss of quality during storage of carambolas. For example, carambolas dipped in hot water at 46°C for 35 or 45 minutes showed increased severity of pitting, bronzing, weight loss, and decay compared to fruit treated with vapor heat at the same temperature and exposure time (Miller and McDonald 2000). ‘Arkin’ carambolas exposed to hot air at 47, 48, and 49°C prior to storage at 4.4°C for 1 or 2 weeks followed by 3 days at 15.6°C showed more severe symptoms of stem-end breakdown and rib-browning, lost more weight, had more undesirable flavor, and deteriorated faster than nonheated fruits (Miller et al. 1990). Likewise, 'Arkin' carambolas dipped in hot water at 49°C for 55 or 70 minutes lost more weight, were duller, and were slightly darker compared to nonheated fruit. Heated fruit developed brown spotting and scalding 2–4 days after the treatment and were considered unmarketable (Hallman 1991). Shelf life of 'Golden Star' and 'Star King' carambolas was significantly reduced when the fruit was immersed in hot water at 49°C for 20–40 minutes. Carambolas developed round black spots 1 or 3 days after immersion in hot water, which rendered the fruits unmarketable (Hallman 1989).

Fruit maturity, storage time, and temperature have a major effect on chemical changes during storage of carambola fruit. As the fruit ripens during storage there is an increase in pH, followed by a reduction in acidity, soluble solids, and sugar contents. After 2 weeks at 5 or 10°C, a gradual decrease in soluble solids content occurred, whereas at 15 and 20°C the decrease was higher and faster. Decrease in total sugars followed a similar pattern, and a significant decrease was observed after 6–8 weeks in mature-green fruit and after 2 weeks in riper fruit (Yon and Jaafar 1994). Sugar content of 'Arkin' and 'Golden Star' carambolas stored at 5 or 10°C remained relatively unchanged during 44 days of storage. However, after transfer to 23°C for 6 days, glucose and fructose contents decreased significantly, particularly in fruit that was stored at 10°C. Acid levels decreased in carambola stored at 10°C for 44 days, but not in fruit held at 5°C for the same period. In fruit stored at 10°C, the initial oxalic and malic acid content dropped by approximately 50% after 44 days (Campbell et al. 1987, 1989).

Time and Temperature Effects on the Visual Quality of 'Arkin' Carambolas

Arkin carambolas shown in Figures 1.59–1.65 were harvested half-ripe (50% yellow) from a commercial operation in Pine Island, Florida, during the spring season (i.e., April). Promptly after harvest, fresh carambolas were stored at five different temperatures (0.5 ± 0.3°C, 5.0 ± 0.2°C, 9.4 ± 0.4°C, 14.40 ± 0.4°C, and 20.0 ± 0.2°C), with 95–98% relative humidity.

Peel injuries, color changes, and decay are the major visual quality defects that develop during postharvest storage of carambolas. 'Arkin' carambolas harvested half-ripe develop a full yellow color after 36, 30, and 16 days at 10, 15, and 20°C, respectively (Figures 1.63–1.65). Conversely, when stored at 0 or 5°C for 38 and 36 days, respectively, carambolas never develop a full yellow color (Figures 1.59 and 1.61).

Arkin carambolas stored at 0°C maintain acceptable visual quality during 38 days of storage, with some minor defects of the peel (i.e., round sunken lesion and subtle rib-edge browning) becoming evident after 20 days of storage (Figure 1.59). However, after transfer for 1 day to 20°C, fruit stored for 4 days at 0°C develops pitting and rib-edge browning that aggravates with exposure time (Figure 1.60). Carambolas stored for 32 days at 0°C plus 1 day at 20°C show severe pitting and browning, whereas the fruit color remains green, indicating that fruit exposed to 0°C is not capable of ripening normally after transfer to nonchilling temperatures.

When stored at 5°C, 'Arkin' carambolas maintain acceptable visual quality during 28 days of storage (Figure 1.61). After that time, some defects develop on the skin of the fruit such as sunken brownish depression on the ribs and browning of the rib edges. After 36 days, a fine mycelium develops in one of the rib edges, adjacent to the stem-end of the fruit. After transfer to 20°C, fruit held for 12 days at 5°C develops pitting and browning of the skin, which aggravates with exposure time to 5°C. In addition, the fruit shows uneven ripening even after transfer to nonchilling temperatures (Figure 1.62).

Arkin carambolas stored at 10°C maintain acceptable visual quality during 24 days of storage (Figure 1.63). After 28 days the fruit develops several areas of sunken brownish discoloration, which increase in size and number as storage progresses. After 32 days, decay develops on the sunken areas of the skin, and on day 36 approximately 50% of the fruit surface is affected by decay. At this temperature, color of the fruit changes from a yellowish-green to full yellow, indicating a normal ripening pattern; yet the riper the fruit the more severe the decay.

Visual quality deterioration of carambolas is rapid when the fruit is stored at 15°C, and postharvest life of the fruit is reduced by the development of browning and decay (Figure 1.64). A brownish sunken lesion on the rib-edge at the blossom-end of the fruit becomes apparent after 4 days and increases in size as storage progresses. After 24 days the stem-end is also affected by a brownish discoloration, and mycelium spreads from the stem-end to the rest of the fruit. Although carambolas develop a full yellow color after 30 days at 15°C, the fruit appears extremely overripe and decayed at this time.

Color of 'Arkin' carambolas changes from a green to fully yellow color after storage for 16 days at 20°C (Figure 1.65). After 20 days decay severely affects the fruit, increases as storage progresses, and after 26 days the fruit in covered by mycelium.

Overall, 'Arkin' carambolas maintain acceptable visual quality when stored at 10°C (24 days), compared to storage at higher or lower temperatures. Fruit stored at 0 and 15°C retains acceptable visual quality during 4 days, whereas visual quality of fruit stored at 5 and 20°C deteriorates after 12 and 16 days of storage, respectively.

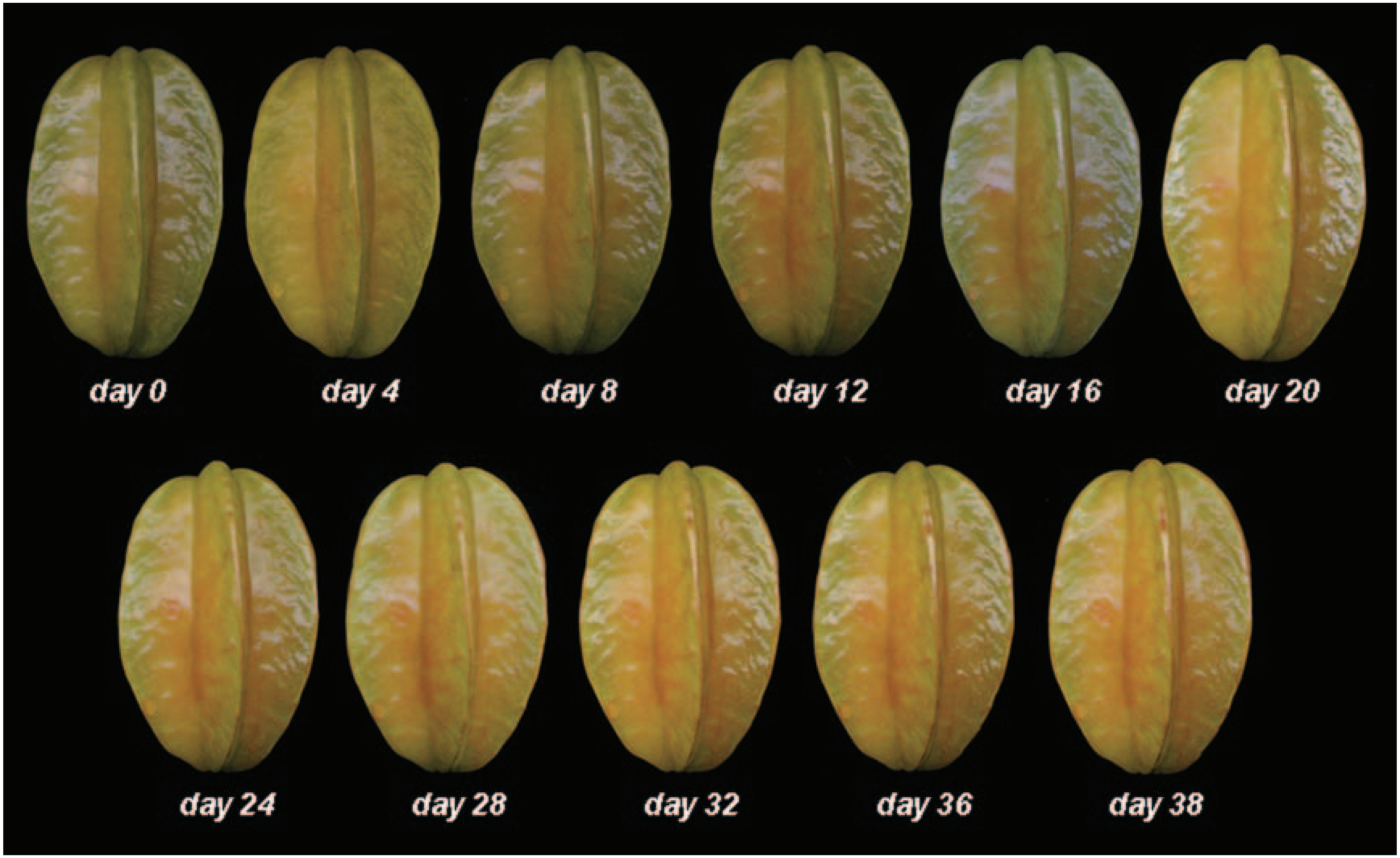
day 0
day 4
day 8
day 12
day 16
day 20
day 24
day 28
day 32
day 36
day 38

Figure 1.59. Appearance of ‘Arkin’ carambola stored for 38 days at 0°C. Some minor defects of the peel are perceptible after 20 days.

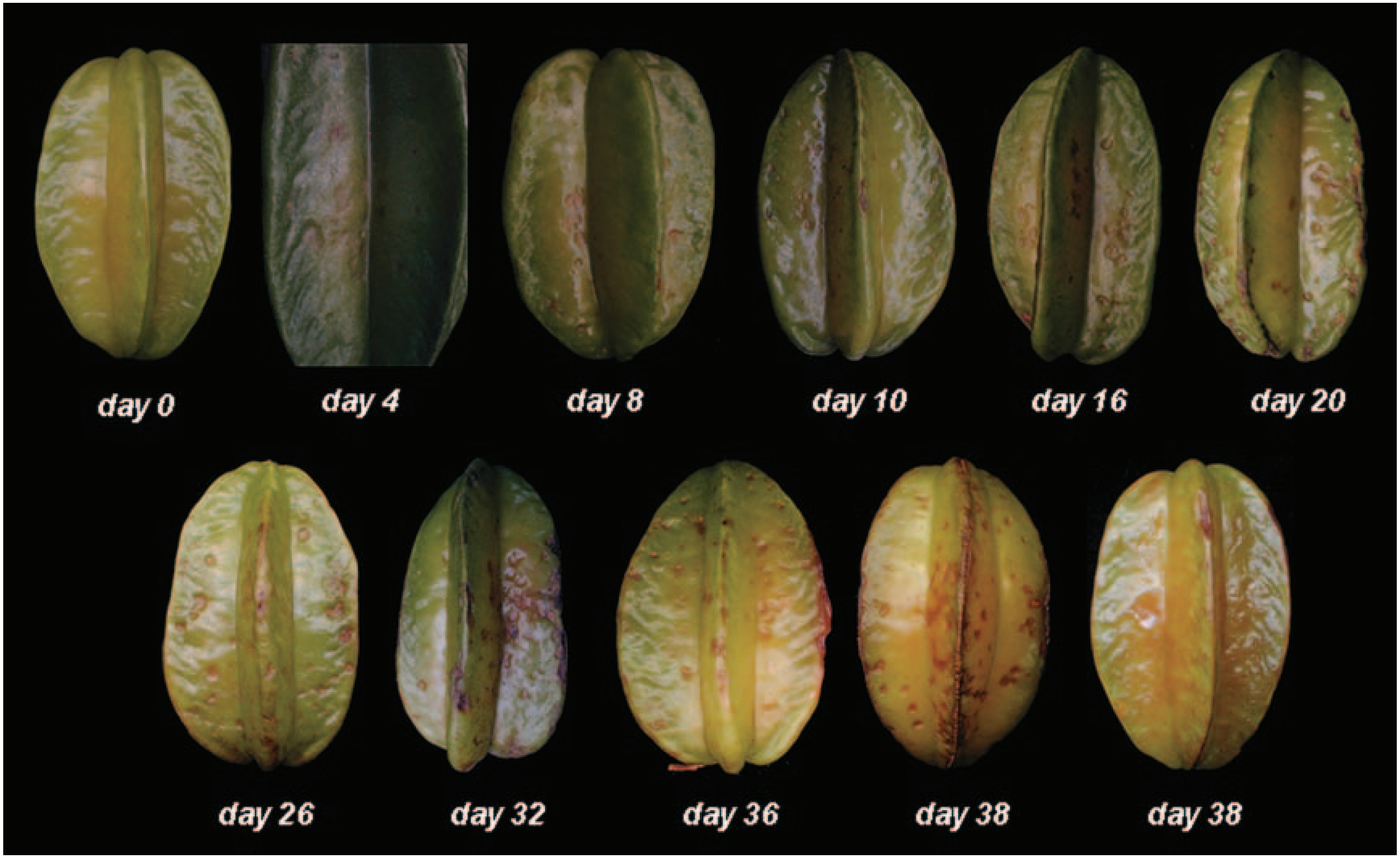
day 0
day 4
day 8
day 10
day 16
day 20
day 26
day 32
day 36
day 38
day 38

Figure 1.60. Chilling injury (pitting and browning of the ribs) in 'Arkin' carambola after storage at 0°C plus 1 additional day at 20°C.

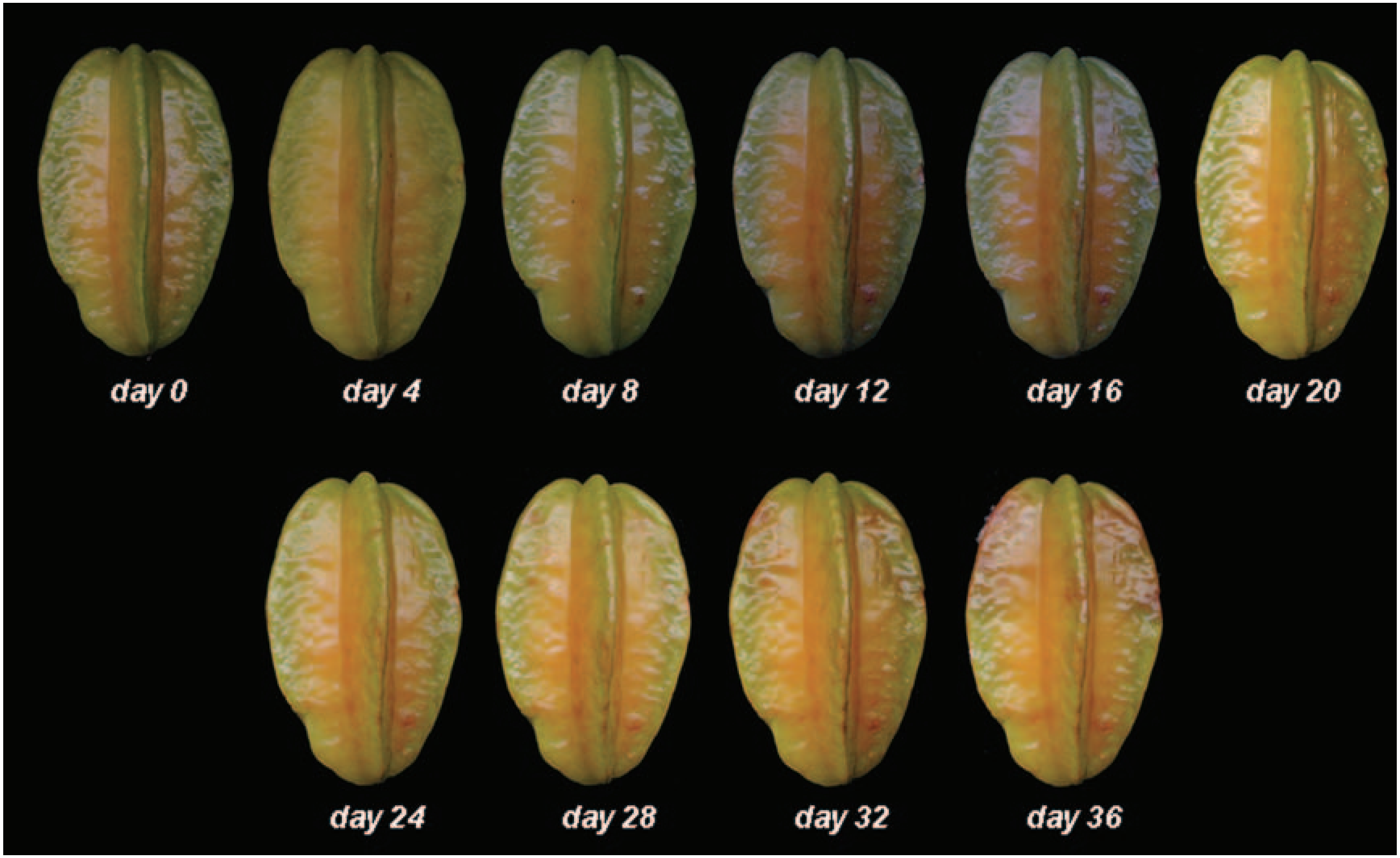
day 0
day 4
day 8
day 12
day 16
day 20
day 24
day 28
day 32
day 36

Figure 1.61. Appearance of 'Arkin' carambola stored for 36 days at 5°C. The fruit maintains acceptable visual quality during 28 days. Slight browning of the peel develops after 32 days.

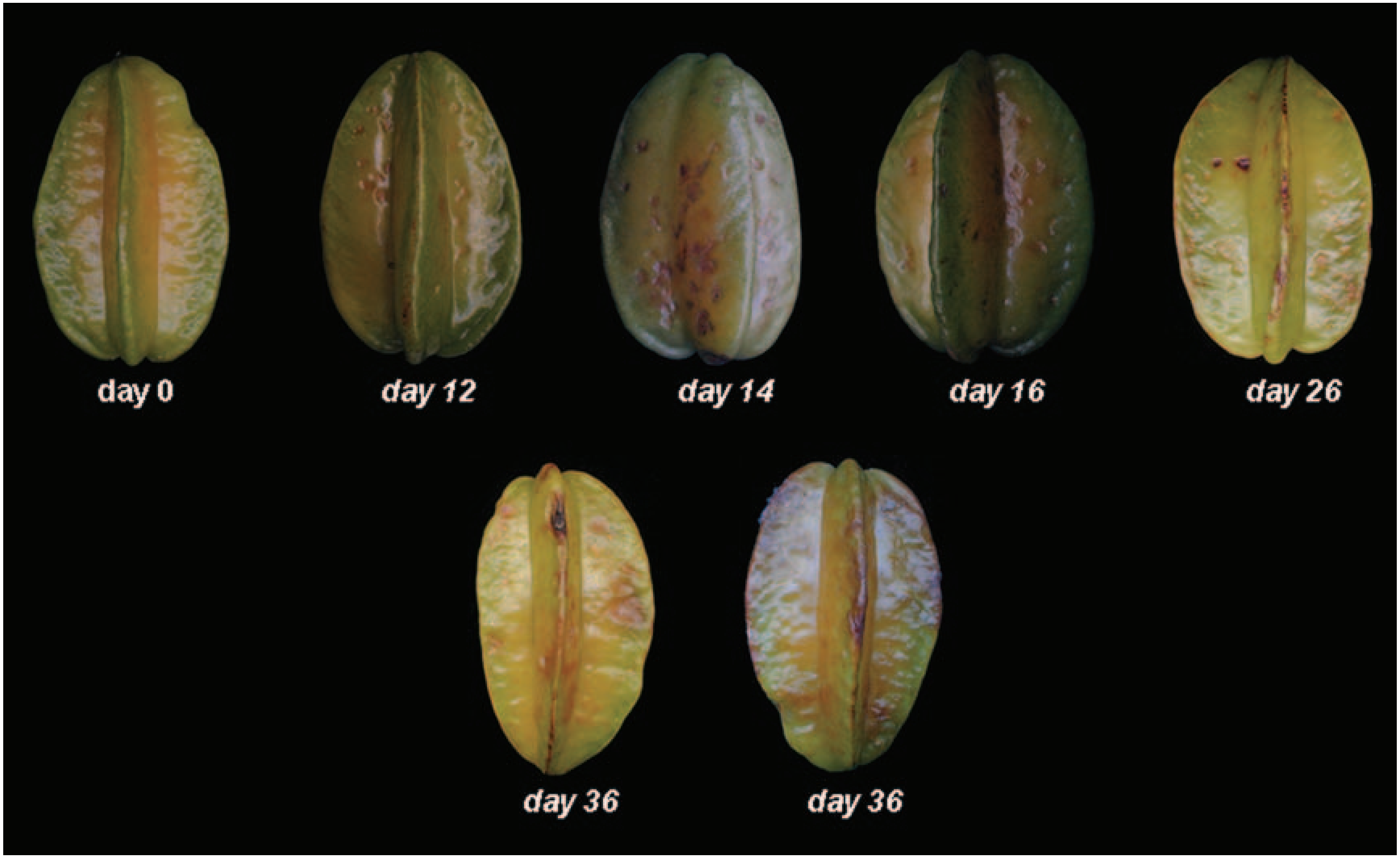
day 0
day 12
day 14
day 16
day 26
day 36
day 36

Figure 1.62. Chilling injury (pitting, browning of the ribs, and uneven ripening) in 'Arkin' carambola after storage at 5°C plus 1 additional day at 20°C.

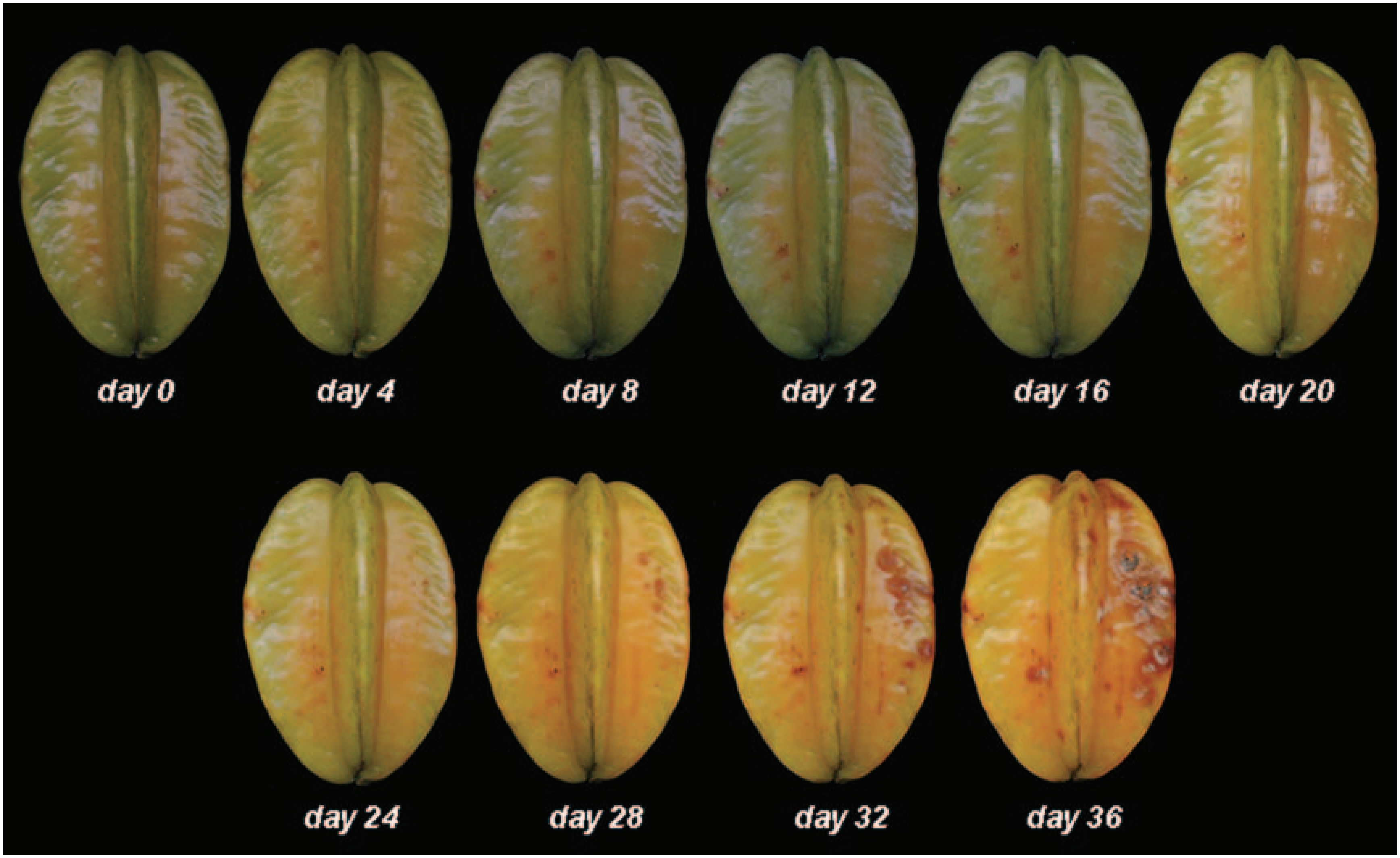
day 0
day 4
day 8
day 12
day 16
day 20
day 24
day 28
day 32
day 36

Figure 1.63. Appearance of 'Arkin' carambola stored for 36 days at 10°C. The fruit maintains acceptable visual quality during 24 days. Slight decay develops after 28 days, and becomes severe after 36 days.

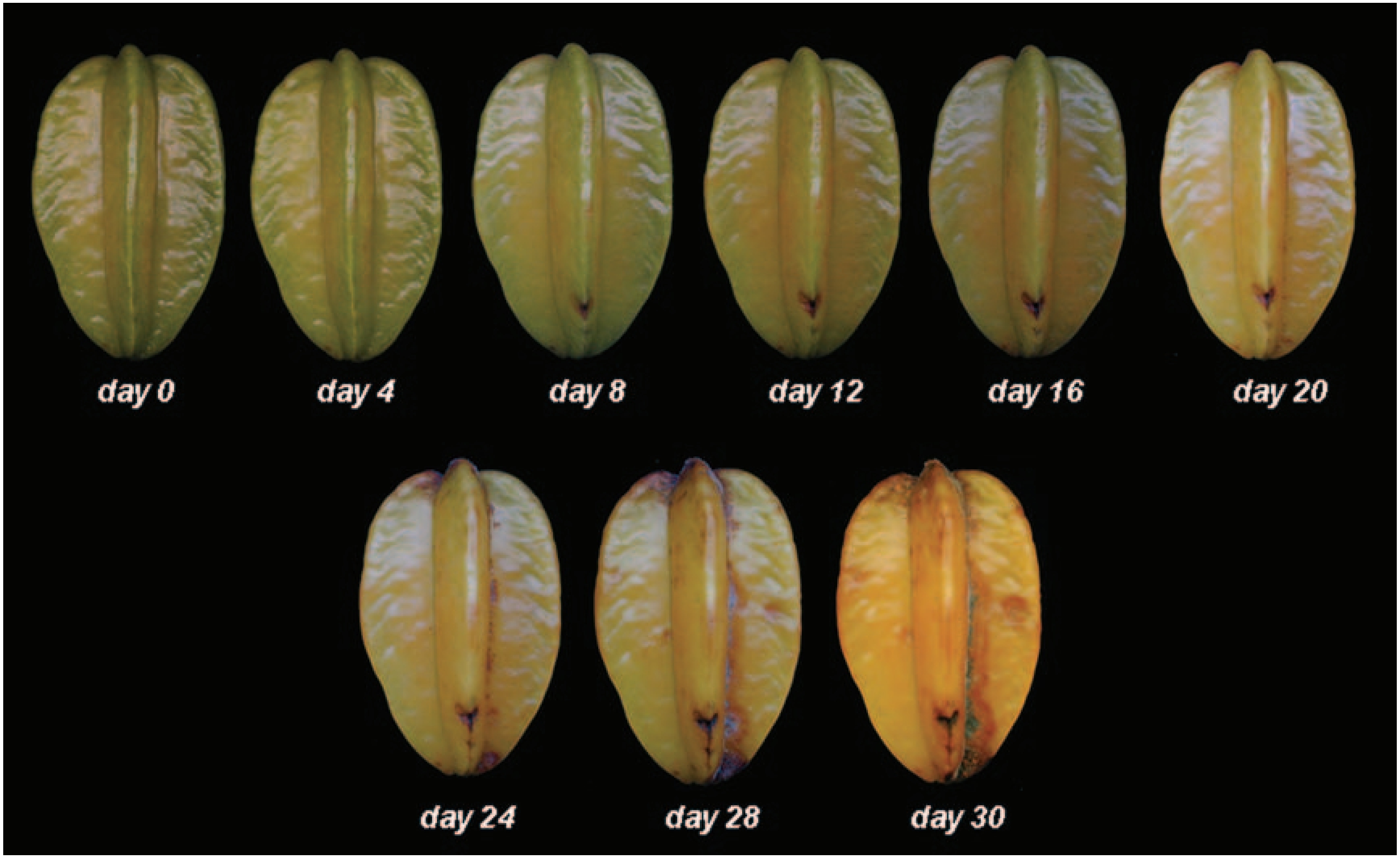
day 0
day 4
day 8
day 12
day 16
day 20
day 24
day 28
day 30

Figure 1.64. Appearance of 'Arkin' carambola stored for 30 days at 15°C. The fruit maintains acceptable visual quality during 4 days. Browning develops after 4 days, and after 28 days browning and decay become objectionable.

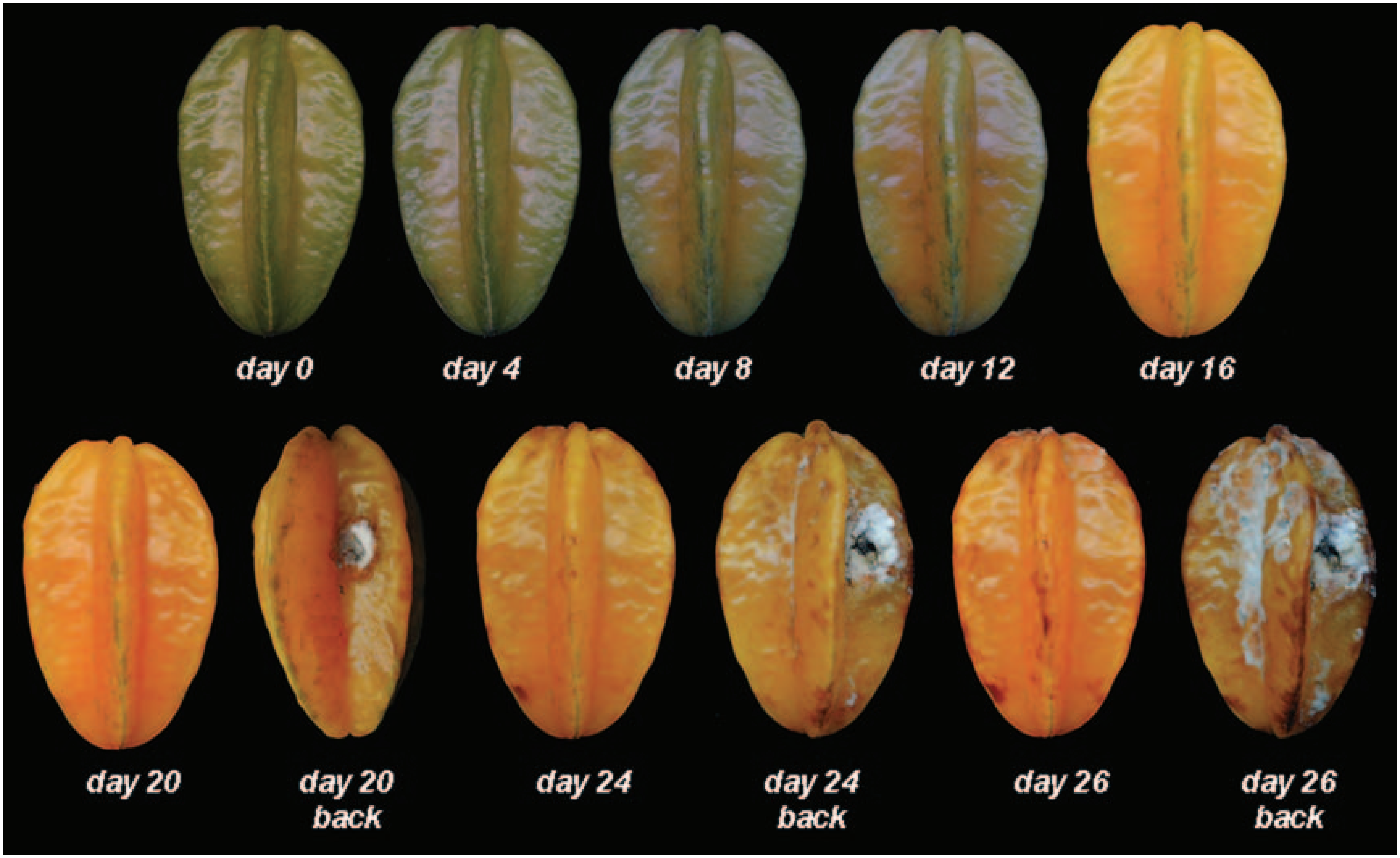
day 0
day 4
day 8
day 12
day 16
day 20
day 20 back
day 24
day 24 back
day 26
day 26 back

Figure 1.65. Appearance of 'Arkin' carambola stored for 26 days at 20°C. The fruit is completely yellow after 20 days but seriously affected by decay.

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CHAPTER 2

POME AND STONE FRUITS

Apple
Peach
Bibliography

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APPLE

Scientific Name: *Malus domestica* Borkh.
Family: Rosaceae

Quality Characteristics

There are many varieties of apples grown in temperate regions worldwide, but 'Golden Delicious,' 'Granny Smith,' 'Red Delicious,' 'Fuji,' 'Gala,' 'McIntosh,' and 'Braeburn' are probably among the most common varieties found in the market. Depending on the variety, color of the skin may range from green to yellow as in 'Granny Smith' and 'Golden Delicious' apples, and to red like in 'Red Delicious' apples. Bi-colored apples include 'Gala,' 'Braeburn,' and 'McIntosh' (Watkins et al. 2004). Although color of the skin is not a good indicator of fruit ripeness or quality, consumer preferences are greatly influenced by the color of the fruit. For example, 'Golden Delicious' apples with a nearly white skin are preferred more than the deep yellow color, although 'Granny Smith' apples with a full green color and 'Red Delicious' with full red color are preferred over partially colored apples (Watkins et al. 2004). Consumer preferences for apples are also based on interactions between texture and taste. For example, some consumers like crisp sweet apples, whereas others like juicy acid apples (Harker et al. 2003).

Fruit texture and firmness are also important quality attributes, as apples that are crispy and crunchy are preferred over soft and mushy fruit, regardless of the variety (Watkins et al. 2004). Nevertheless, apple texture and flesh firmness vary with the type of cultivar, some apples being softer than others. Flesh firmness of different apple cultivars has been reported to range from 36.9 N (Newtons) in 'Cox's Orange Pippin' and 49.5 N in 'Jonagold' to 95.5 N in 'Gala' and 130.3 N in 'York' (Gheyas et al. 1997; Harker et al. 2002a; Rizzolo et al. 2006). A difference of 6 N was reported to be the least difference in fruit firmness that could be detected by an individual (Harker 2002a).

Like flesh firmness, sweetness and acidity also depend on apple variety. Acidity ranges from 0.8 to 1.2% in 'Granny Smith' and from 0.2 to 0.4% in 'Red Delicious,' whereas soluble solids content ranges from 9% in 'Red Delicious' to 17–20% in 'Fuji' (Gheyas et al. 1997; Rizzolo et al. 2006; Watkins et al. 2004). Overall, apple quality consists of a mixture of several factors such as visual appearance, texture, and flavor (including soluble solids, acidity, and volatiles) (Mitcham et al. 2006; Watkins et al. 2004). The soluble solids content of the fruit was reported to be a good predictor of apple fruit sweetness, whereas differences in acidic taste were well correlated with titratable acidity (Harker et al. 2002b). During ripening of 'Royal Gala' apples a linear decrease in starch was observed, whereas the soluble solids content did not change significantly (Stow and Genge 2000). Likewise, as 'McIntosh' apples changed from immature to fully mature, starch content decreased, whereas a 44% increase in soluble solids content and a 23% decrease in acidity were observed (Marmo et al. 1985). In 'Fuji' and 'Royal Gala' the decrease in starch content parallels the development of red coloration (Brookfield et al. 1997). Apple position on the tree also has a great influence on fruit ripening, color development, and fruit composition. For example, 'Aroma' apples from outside positions on a tree were in general more red and had higher soluble solids and sugar contents and lower acidity than fruit from the inside positions on the same tree (Nilsson and Gustavsson 2007). Apple flavor also increases as the fruit matures, but fruit from very late harvests showed a tendency to have a lower concentration of volatiles, compared to that harvested at the optimum harvest date (Yahia 1994). Total phenolics concentration decreases during the earlier stages of maturation, but then remains constant until the fruit has attained harvest maturity (Coseteng and Lee 1987).

On average, apple fruit contain 86% water, 14% carbohydrates, 0.3% proteins, 0.9–3.6% fiber, 27 μg of β-carotene, and 3–13 mg of vitamin C per 100 g of fresh fruit (Davey et al. 2007; Gheyas et al. 1997; Gorinstein et al. 2001; Meberg et al. 2000; USDA 2006).

Optimum Postharvest Handling Conditions

To avoid major loss of quality during storage, apple fruit should be promptly cooled after harvest. Delay in cooling affects the firmness of the fruit and reduces its postharvest life. In addition, apples cooled to 0°C immediately after harvest were firmer when compared to delay-cooled fruit (D'Souza and Ingle 1989). A 7- to 10-day reduction in postharvest life was observed in 'McIntosh' apples held for 1 day at 21°C before cooling, compared to promptly cooled fruit. Rapid cooling after harvest is also very important, as it prevents shriveling and softening, particularly in ‘Golden Delicious’ and ‘Gala’ apples (Mitcham et al. 2006). Although prompt cooling after harvest is recommended for most apple cultivars, some cultivars that are more susceptible to scald and low-temperature breakdown can benefit from a delay before cooling. For example, ‘Honeycrisp’ apples held for 7 days at 20°C prior to storage at 3 or 5°C showed a significant reduction in soft scald and low-temperature breakdown following 4–6 months of storage, compared with fruit immediately cooled to 5°C after harvest (DeLong et al. 2004). After pre-cooling, most apples can be stored between 1°C and 4°C and 90 and 95% humidity, depending on the variety. When stored at 0°C, an average postharvest life of 2–4 months is expected, depending on the variety (Watkins et al. 2004). ‘Red Delicious,’ ‘Golden Delicious,’ ‘Fuji,’ and ‘Gala’ apples should be stored at 0–1°C with 90–95% humidity. Some apple varieties such as ‘Granny Smith,’ ‘McIntosh,’ and ‘Honeycrisp’ may be susceptible to develop low-temperature injury when stored at 0°C. Therefore, recommended storage temperatures range from 1 to 5°C (DeLong et al. 2004; Fidler and Wilkinson 1973; Mitcham et al. 2006).

Temperature Effects on Quality

To provide the market with a year-round supply of apples, fruit is seldom consumed immediately after harvest and is stored for periods of up to 6 months. During that extended storage period, major losses in quality may occur if the fruit is not maintained under adequate conditions. Fruit losses can result from decay, superficial scald, bitter pit, internal browning, water core, and skin shriveling owing to increased water loss (Davey et al. 2007). In addition, changes in color, firmness, texture, flavor, and composition are also important causes of apple quality loss. Changes in apple coloration that occur during the postharvest period are a result of chlorophyll breakdown and biosynthesis of pigments such as anthocyanins. Anthocyanins may be present or absent in the skin of apple fruit. If anthocyanins are absent, the fruit may be completely yellow or green. If anthocyanins are present, the skin of fruit may show different patterns, from small red flecks to bold stripes, and from a slight blush to a full red color (Janick et al. 1996).

Changes in fruit coloration may occur even when the fruit is detached from the tree. Chlorophyll concentration in green apples decreases exponentially with time, and the decrease is faster at higher temperatures. Consequently, skin yellowing of ‘Granny Smiths’ and ‘Cox’s Orange Pippins’ was shown to increase slowly as the temperature increased from 0 to 5°C, increase exponentially from 5 to 20°C, reach a maximum from 20 to 25°C, and then decline at higher temperatures (30–35°C) (Dixon and Hewett 1998). Similarly, the color of ‘Golden Delicious’ apple cultivars stored at 20°C for 30 days became lighter, less green, and more yellow (Rizzolo et al. 2006). In red-colored apple cultivars the development of red color is due to the increase in anthocyanin concentration and is directly related to the levels of the pigments in the skin. Furthermore, accumulation of anthocyanins in the skin of apple fruit is greatly influenced by light. For example, ‘Royal Gala’ exposed to white or ultraviolet (UV) light showed an increase in red color and anthocyanin concentration after 6 days at 14°C, compared to fruit stored in the dark. During long-term storage, an optimum combination of UV light and storage at 4°C has been suggested, as such conditions contribute to the biosynthesis and accumulation of anthocyanins in the skin of ‘Royal Gala’ apples (Dong et al. 1995).

Rapid softening during storage is a detrimental attribute in apples because fruit that is soft is in most cases rejected. Temperature has a great influence on apple flesh softening, and, in general, firmness decreases with storage time and temperature. Apple softening patterns are, however, dependent on the storage temperature. That is, fruit softens differently depending on the temperature. For example, ‘Royal Gala’ stored between 0 and 5°C, ‘Cox’s Orange Pippin’ stored between 0 and 2.5°C, and ‘Granny Smith’ and ‘Pacific Rose’ stored between 0 and 12°C showed a phase of little or no flesh firmness decrease for the first 5–25 days of storage. After that period a phase of rapid loss of firmness occurred, followed by a final phase of little or no firmness loss. However, in apples stored at temperatures higher than 12°C, only the rapid and final slow softening phases were evident (Johnston et al. 2001b, 2002). Firmness of four apple cultivars stored for 12 months at 0°C significantly decreased during storage from values of about 105 N at harvest to less than 60 N after 12 months of storage (Saftner et al. 2005). Flesh softening of ‘Royal Gala’ stored at 0 or 1.5°C significantly increased during storage, and after 10 weeks the fruit was considered unacceptable due to loss of firmness (Stow and Genge 2000). Firmness of ‘Golden Delicious’ apples stored for 6 months at 1°C significantly decreased during storage, from initial values of 70 N to less than 40 N after 6 months (Siddiqui et al. 1996). Similarly, when ‘Pink Lady’ apples were stored for 25 weeks at 1°C, and then transferred to 20°C for 7 days, firmness significantly decreased from an initial value of 91.7 N to 74.8 N after storage (López et al. 2007).

Apple fruit may develop certain types of skin and flesh disorders during prolonged storage under inadequate conditions. For example, scald and low-temperature breakdown may develop in some apple cultivars when exposed to chilling temperatures for extended periods. Superficial scald is characterized by browning of the skin, which develops during prolonged low-temperature storage in some apple varieties (Mitcham et al. 2006; Watkins et al. 1995). The disorder is thought to be induced by chilling injury (CI), when apples are exposed to low temperatures. For example, ‘Granny Smith’ apples stored for 30 weeks at 0 or 4°C developed characteristic symptoms of superficial scalding, whereas fruit stored at 15 or 20°C showed no scalding. The incidence of scalding decreased with increasing temperature, as 100% of the fruit stored at 0°C showed scald, whereas it developed in only 87% of the fruit stored at 4°C. Warming the fruit for 3–5 days at 20°C after exposure for

2 weeks at 0°C reduced the incidence and severity of scalding (Watkins et al. 1995). Low-temperature breakdown is characterized by the development of brown vascular bundles, browning of the flesh, and a clear halo of unaffected tissue underneath the skin. Contrary to senescent breakdown, the tissues may maintain their firmness and moisture content and be darker in color (Watkins et al. 2004).

Some apple varieties such as ‘Granny Smith’ are highly susceptible to development of bitter pit during storage. The disorder is characterized by brown, corky, round lesions on the skin, particularly at the calyx end. Large fruit from young trees is the most susceptible, and the disorder is related to low calcium concentrations in the fruit. Therefore, preharvest calcium sprays or postharvest calcium dips have been used to prevent the development of the disorder during storage (Mitcham et al. 2006).

Apple water core is characterized by water-soaking of the flesh near the core owing to the accumulation of sorbitol in the intercellular spaces, resulting in internal browning and breakdown (Mitcham et al. 2006). Internal breakdown is often seen in senescent apples. The fruit flesh becomes off-white to yellow, and then brown and mealy. In advanced stages, the skin is also discolored and the flesh is soft. Large apples, late harvest, delayed cooling, and high storage temperatures contribute to apple premature breakdown from water core (Anonymous 1982; Marmo et al. 1985).

‘Golden Delicious’ apples are particularly susceptible to water loss and shriveling during storage. Because of water loss the weight of the fruit can be reduced by 3–6% (Mitcham et al. 2006). Development of shriveling during storage of apples is greatly dependent on loss of moisture. In general, loss of moisture, and, consequently, loss of fruit weight increases as storage time and temperature increase. In ‘Aroma’ apples grown in Norway, weight loss after approximately 4 months at 2°C was 1.7%. However, when the fruit was transferred to 20°C for 1 additional week, weight loss increased significantly to 5.4% (Meberg et al. 2000). Weight loss of ‘Royal Galas’ stored at 20°C for only 1 day was almost two times higher (approximately 3%) than weight loss of fruit stored at 0°C (approximately 1.5%). In addition, when fruit skin was partially removed before the fruit was held for 1 day at 0°C, weight loss was significantly higher (greater than 5%) than in intact fruit stored under the same conditions (Johnston et al. 2001a).

Storage temperature and duration have a great effect not only on the appearance and texture of apple fruit but also on the composition. In general, soluble solids, acidity, and ascorbic acid contents decrease, whereas pH increases during storage, regardless of the temperature (Davey et al. 2007; López et al. 2007; Meberg et al. 2000; Nilsson and Gustavsson 2007; Saftner et al. 2005). For example, soluble solids content, acidity, and volatile contents of four apple cultivars decreased during storage for 12 months at 0°C, whereas soluble solids contents-to-acidity ratios increased (Saftner et al. 2005). Likewise, ‘Aroma’ apples grown in Norway and stored for approximately 4 months at 2°C showed decreases in soluble solids content and acidity and increases in pH and soluble solids content-to-acidity ratio during storage. Ascorbic acid content also decreased during storage from an initial value of 9.8 mg to 3.6 mg per 100 g fresh weight after approximately 4 months at 2°C. Upon transfer of the fruit to 20°C for 1 additional week, ascorbic acid further decreased to 3.0 mg per 100 g fresh weight (Meberg et al. 2000). Likewise, ascorbic acid content of several apple cultivars decreased from an average of 5.9–14.5 mg per 100 g fresh weight to about 3.3–13.1 mg per 100 g fresh weight when apples were held for 10 days at 20°C. Therefore, some cultivars lost approximately 82% of their initial total ascorbic acid content after shelf life (Davey et al. 2007). Conversely, increases in carotenoid content of apples was observed during storage for 3–4 weeks at 25°C (Solovchenko et al. 2005). Sugar content and flavor volatiles of ‘Royal Galas’ stored at 0 or 1.5°C decreased during storage (Stow and Genge 2000). However, total volatile content of ‘Golden Delicious’ apples increased compared to initial values after storage for 30 days at 20°C (Rizzolo et al. 2006).

Time and Temperature Effects on the Visual Quality of ‘Golden Delicious’ and ‘McIntosh’ Apples

‘Golden Delicious’ and ‘McIntosh’ apples shown in Figures 2.1–2.11 were harvested at the commercial harvest maturity from a commercial operation in Farnan, Quebec, Canada, during the fall season (i.e., October). Promptly after harvest, fresh apples were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Color of ‘Golden Delicious’ apples changed during storage, regardless the temperature, from a greenish-yellow to a deeper yellow color. However, changes were faster in fruit stored at temperatures higher than 5°C. Similarly, severity of shriveling increased with increasing temperature and length of storage.

Color of ‘Golden Delicious’ apples stored at 0°C changes from a greenish-yellow at the time of harvest to yellow after 48 days of storage, and after 148 days the fruit color turns deep yellow. Parallel to changes in color of the fruit skin, shriveling increases from slight to moderate during 138 days of storage. After 166 days of storage shriveling attains moderate to severe levels, yet internal quality of the fruit remains acceptable (Figure 2.1).

Apples stored at 5°C maintain acceptable visual quality during up to 124 days of storage, but after that time the fruit becomes shriveled. Color of the fruit also changes during storage from a yellowish-green to yellow, and after 131 days of storage the fruit develops a deep yellow color and slight to moderate shriveling. Although shriveling becomes objectionable after 138 days of storage, internal quality of the fruit remains acceptable (Figure 2.2).

Apples stored at 10°C maintain an acceptable visual quality for up to 32 days, but after that time color changes from a yellowish-green to a deeper yellow and shriveling becomes evident after 48 days. After 72 days of storage, shriveling attains unacceptable levels and the fruit appears very shriveled, yet the internal quality of the fruit remains acceptable (Figure 2.3).

Changes in color from yellowish-green to yellow and development of shriveling are faster at 15°C compared to lower temperatures. Apples develop a full yellow color after 24 days of storage and become severely shriveled after 52 days. Internal quality of the fruit remains acceptable after 52 days of storage despite shriveling (Figure 2.4).

Within 16 days, the color of 'Golden Delicious' apples stored at 20°C changes from a yellowish-green to a deep yellow color, and after 24 days the fruit appears shriveled. Internal quality of the fruit remains acceptable during 40 days of storage despite the severe shriveling of the skin (Figure 2.5).

Overall, changes in color from green to deep yellow and development of shriveling are the major visual quality changes that occur during storage of 'Golden Delicious' apples. Increasing the time and storage temperature accelerates the rate of visual color changes. The higher the storage temperature the shorter the time the visual quality of apple fruit remains acceptable. 'Golden Delicious' apples maintain better visual quality for a longer time when stored at 0°C (148 days), compared to storage at higher temperatures. Visual quality of 'Golden Delicious' apples remains acceptable up to 124, 32, 24, and 16 days at 5, 10, 15, and 20°C, respectively, but deteriorates rapidly afterward.

'McIntosh' apples are relatively less susceptible than 'Golden Delicious' apples to changes in color and to development of shriveling when stored under similar conditions. Apples stored at 0°C show subtle color changes or signs of shriveling during storage, whereas fruit stored at higher temperatures shows slight to moderate color changes and shriveling during storage. Although no major changes occur in the red-colored surface area of 'McIntosh' apples stored at temperatures below 10°C, the initially green-colored surface area of the fruit becomes more yellowish, and the fruit appears less shiny as storage time and temperature increase. Although 'McIntosh' apples stored at 0°C maintain acceptable external quality up to 166 days of storage, the fruit loses its initial red glossy color and appears dull. The fruit maintains acceptable external quality during up to 166 days of storage; however, when stored for 148 days at 0°C internal breakdown develops upon transfer of the fruit to 20°C for 2 additional days (Figure 2.6).

'McIntosh' apples stored at 5°C maintain acceptable visual quality during 124 days of storage, after which the fruit loses its red glossy color and becomes dull. Shriveling also develops after 124 days, becoming objectionable after 138 days of storage, yet the internal quality of the fruit remains acceptable (Figure 2.7).

Changes to the visual appearance of apples occurs faster when fruit is stored at 10°C, and after 78 days the green-colored surface area of the fruit becomes less green and more reddish-yellow. Simultaneously, the fruit loses its gloss and becomes dull. After 96 days of storage, signs of shriveling become evident, and after 105 days the fruit appears extremely shriveled, yet the internal quality of the fruit remains acceptable (Figure 2.8).

Visual quality of 'McIntosh' apples stored at 15°C deteriorates rapidly, and after only 16 days the fruit loses its greenish-red glossy color and becomes more red and dull. Shriveling becomes evident after 40 days of storage and some internal brownish-red discoloration is also noticeable (Figure 2.9).

The green-colored area of the fruit disappears completely during storage and becomes yellowish-red in fruit stored for 44 days at 20°C. However, at this time the fruit looks extremely shriveled and less shiny, yet the internal quality remains acceptable (Figure 2.10). Some disorders also develop when 'McIntosh' apples are exposed to 20°C for extended periods. Figure 2.11 shows bitter pit in 'McIntosh' apples after 40 days of storage at 15°C, and extreme decay and internal breakdown in apples stored for 40 days at 20°C.

Overall, changes in color from a shiny greenish-red to a dull yellowish-red and development of shriveling are the major external visual quality changes that occur during storage of 'McIntosh' apples. However, internal quality is also affected by storage temperature. Increasing the storage time and temperature accelerates the rate of visual quality changes. 'McIntosh' apples maintain better external visual quality for a longer period when stored at 0°C (138 days). However, when stored for more than 138 days at 0°C, internal breakdown is more likely to occur during storage owing to the fruit sensitivity to low temperatures. Fruit visual quality remains acceptable during 124, 78, 40, and 24 days when 'McIntosh' apples are stored at 5, 10, 15, or 20°C, respectively, but deteriorates rapidly if storage is prolonged.

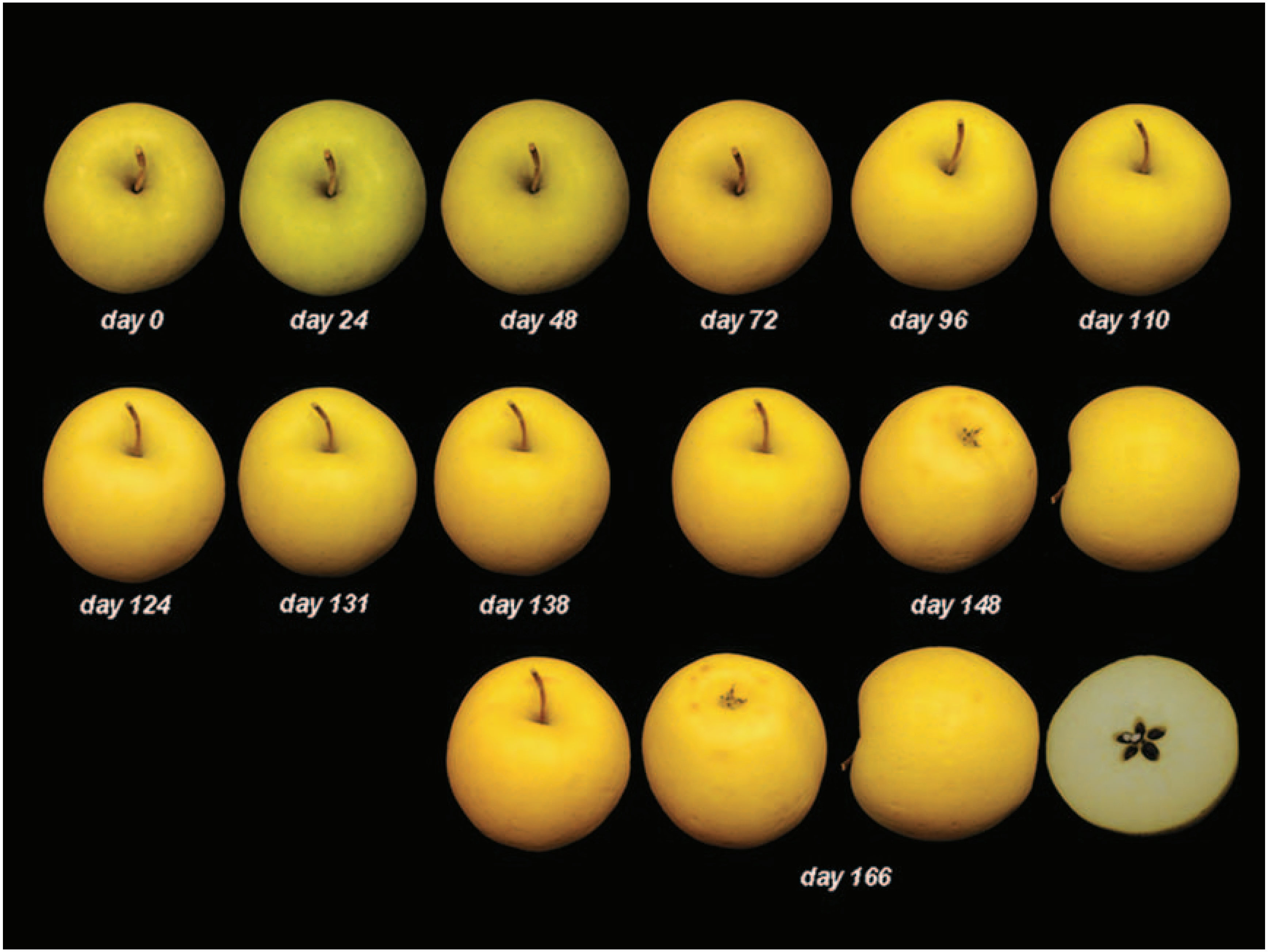
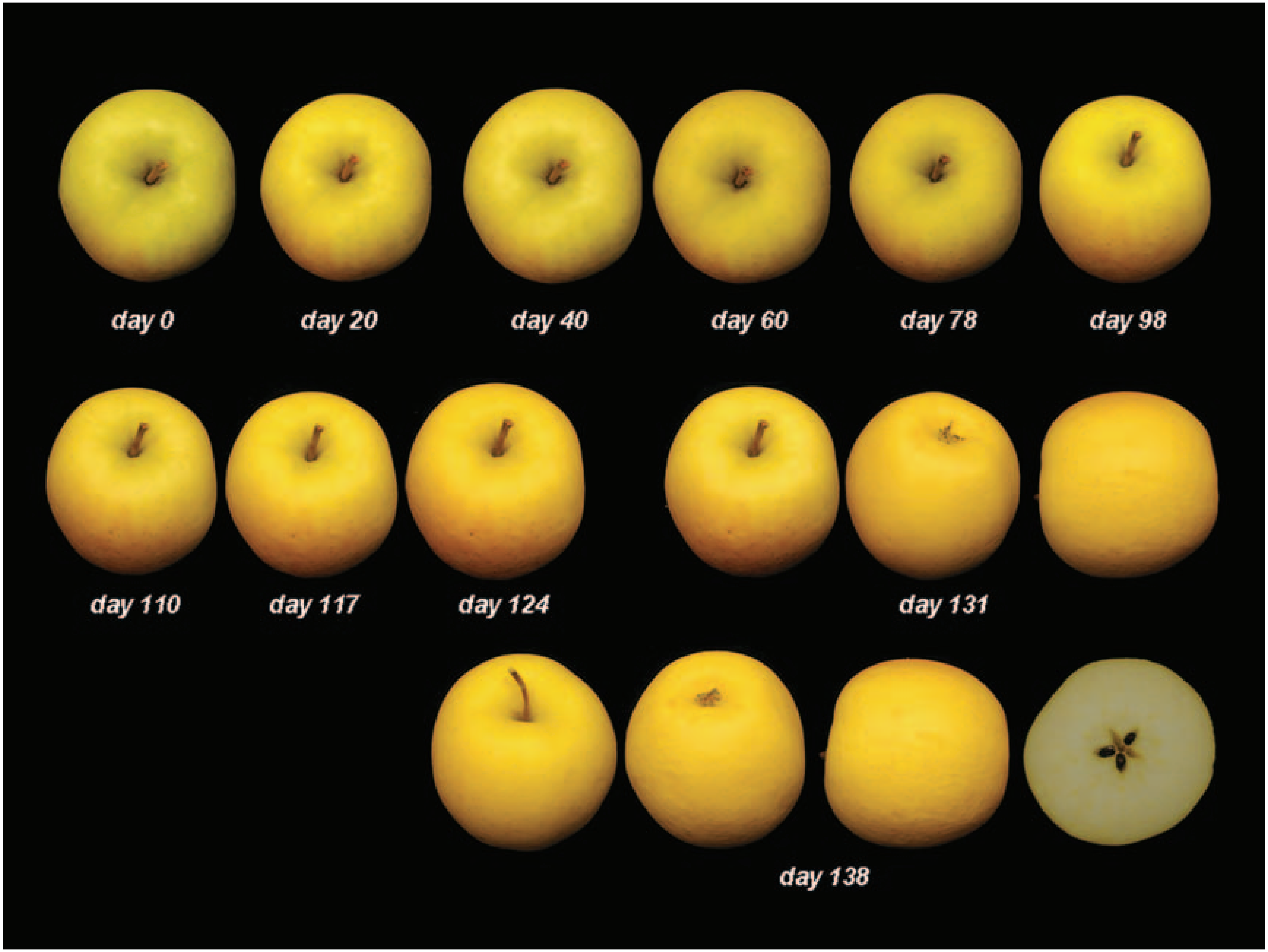

day 0
day 24
day 48
day 72
day 96
day 110
day 124
day 131
day 138
day 148
day 166

Figure 2.1. Appearance of 'Golden Delicious' apple stored for 166 days at 1°C. After 48 days of storage the color of the fruit starts to change from a greenish-yellow to yellow, and after 148 days the color of the fruit is of a deep yellow. After 138 days fruit shriveling becomes evident.


day 0
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day 40
day 60
day 78
day 98
day 110
day 117
day 124
day 131
day 138

Figure 2.2. Appearance of ‘Golden Delicious’ apple stored for 138 days at 5°C. Apple develops a deeper yellow color during storage, and after 131 days shriveling becomes evident.

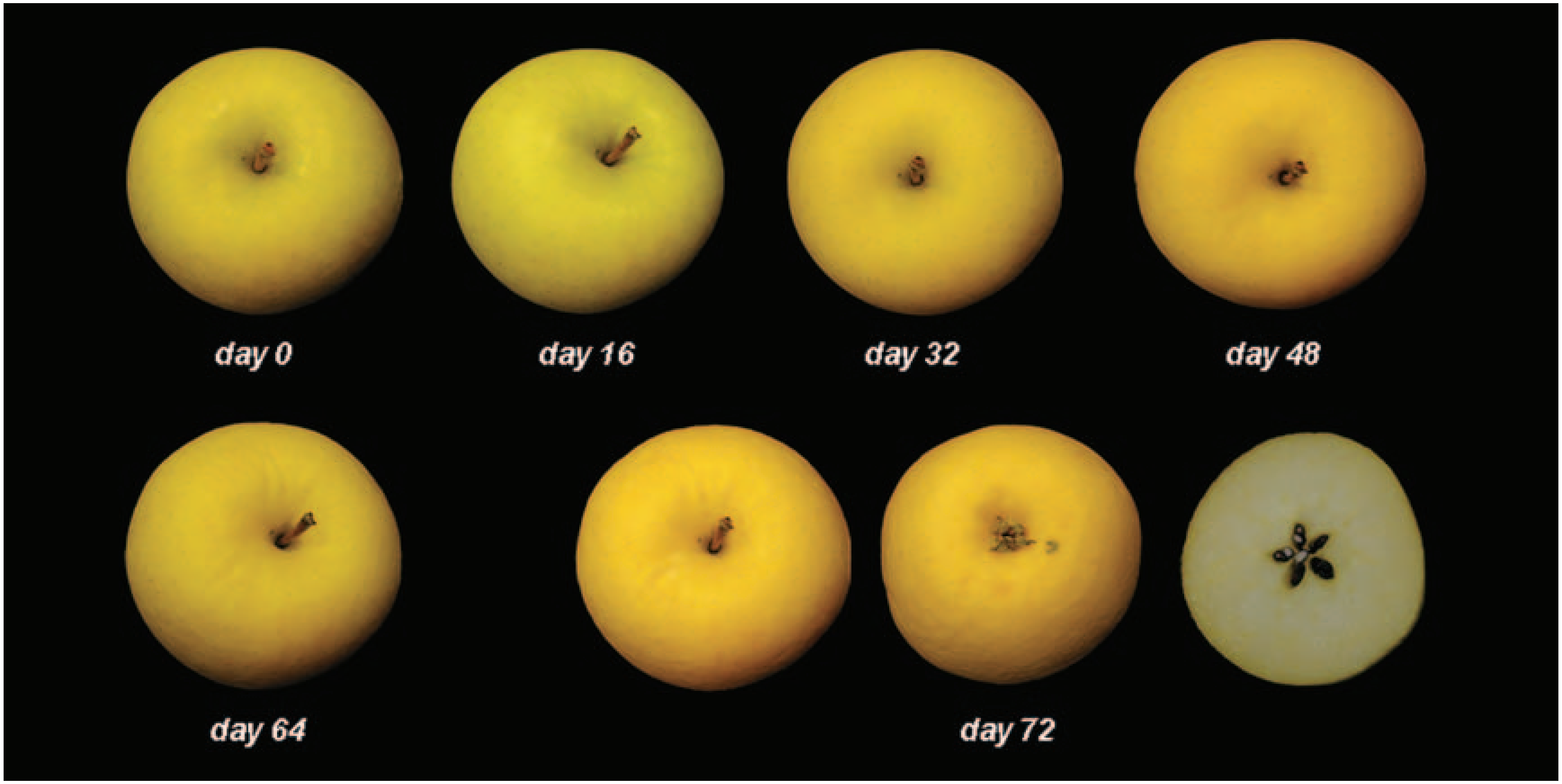
day 0
day 16
day 32
day 48
day 64
day 72

Figure 2.3. Appearance of ‘Golden Delicious’ apple stored for 72 days at 10°C. Apple develops a deeper yellow color during storage, and after 48 days shriveling becomes evident. Fruit stored for 72 days appears extremely shriveled and soft.

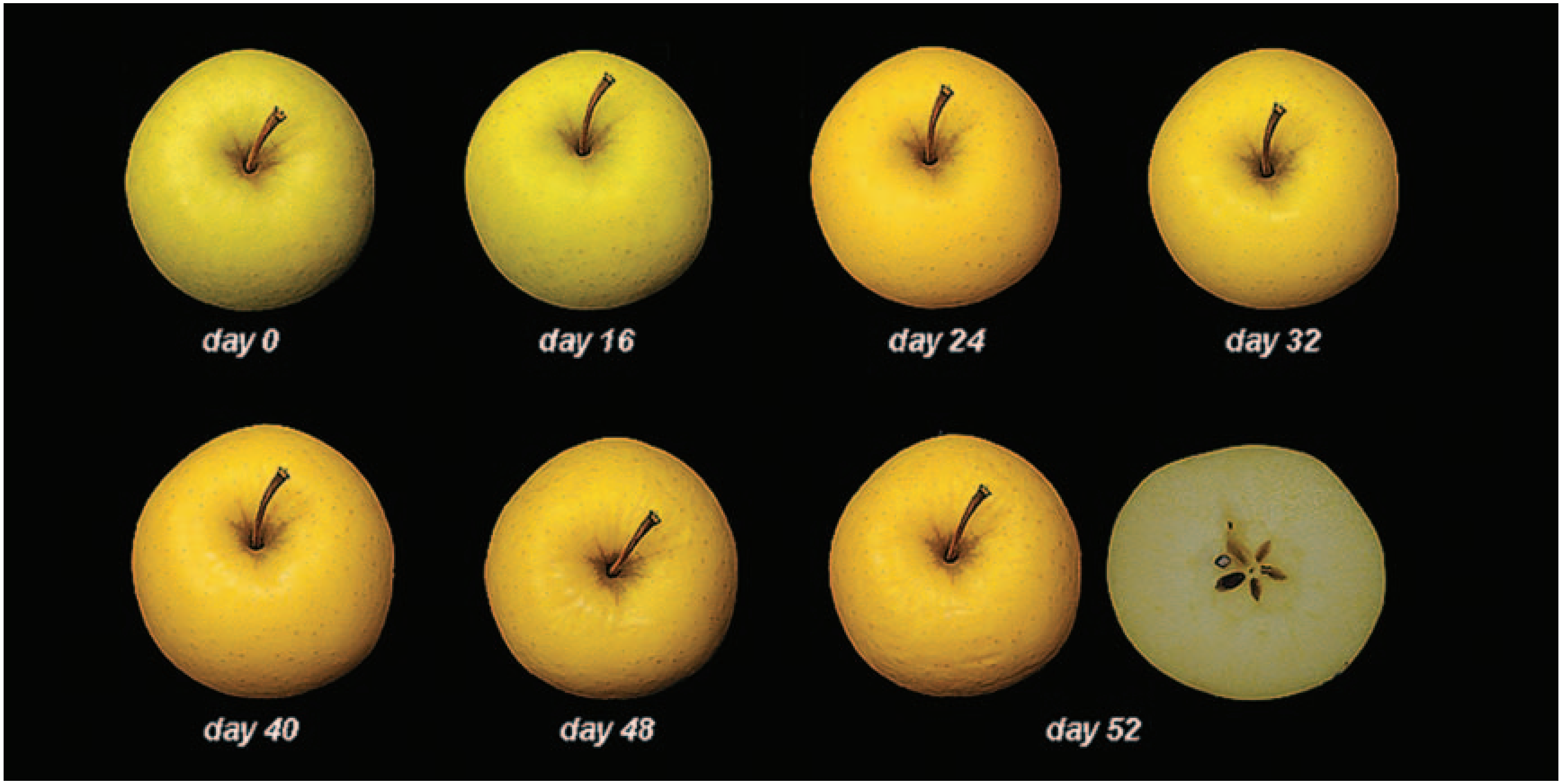
day 0
day 16
day 24
day 32
day 40
day 48
day 52

Figure 2.4. Appearance of 'Golden Delicious' apple stored for 52 days at 15°C. After 16 days the color changes from a greenish-yellow to a deeper yellow, and after 48 days the fruit appears extremely shriveled.

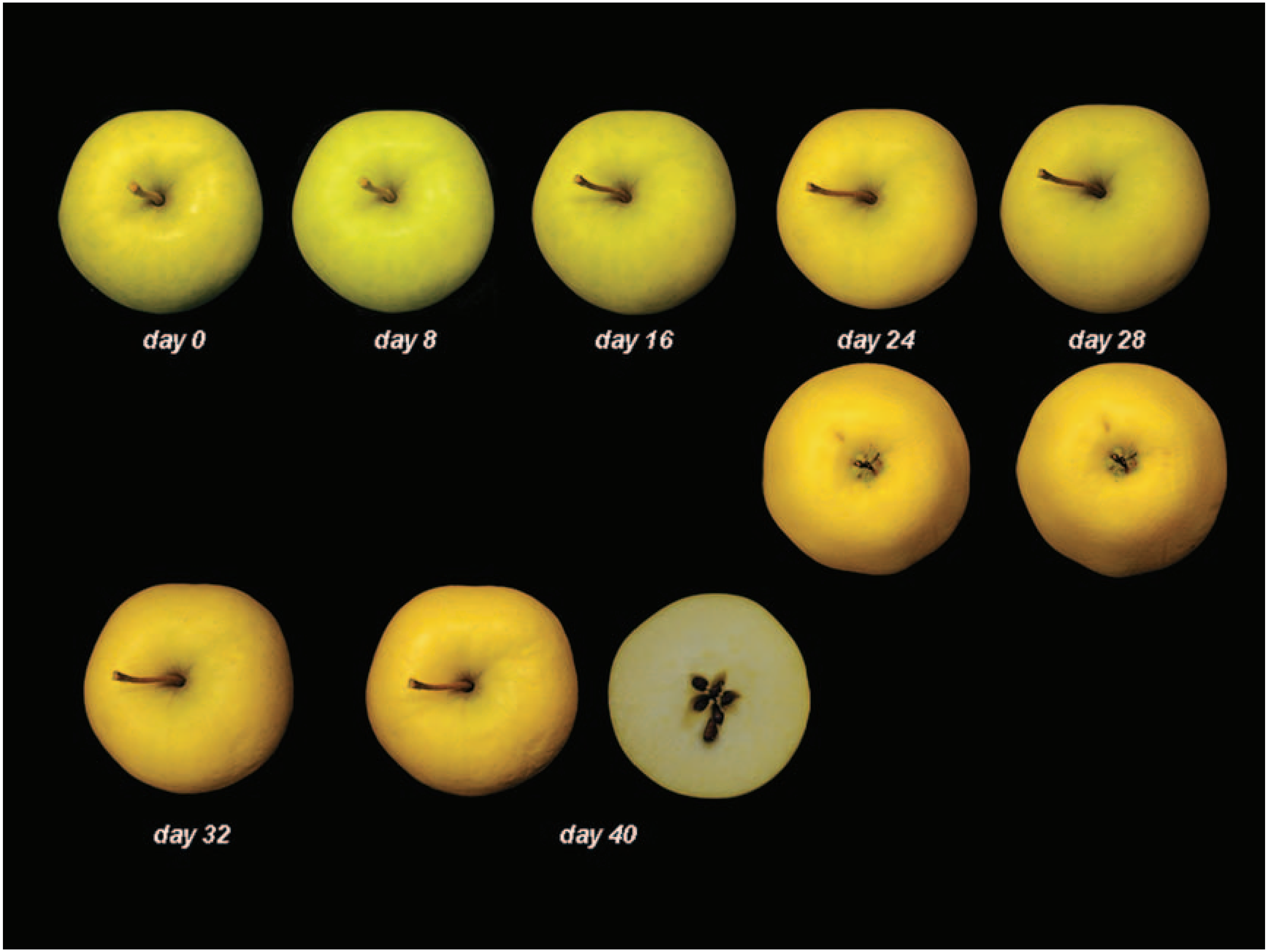
day 0
day 8
day 16
day 24
day 28
day 32
day 40

Figure 2.5. Appearance of 'Golden Delicious' apple stored for 40 days at 20°C. After 16 days the color changes from a greenish-yellow to a deeper yellow, and after 40 days the fruit appears extremely shriveled.

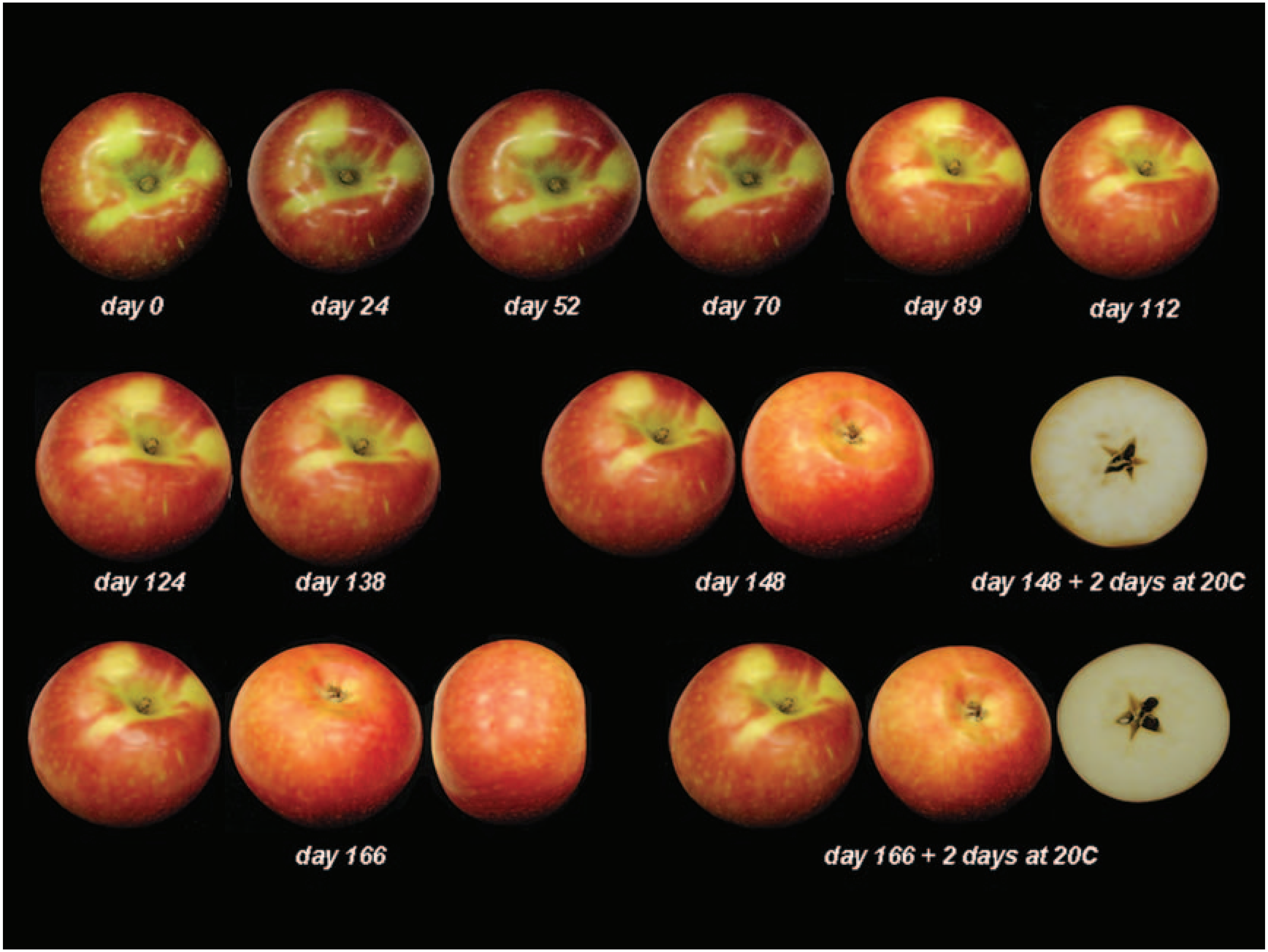
day 0
day 24
day 52
day 70
day 89
day 112
day 124
day 138
day 148
day 148 + 2 days at 20C
day 166
day 166 + 2 days at 20C

Figure 2.6. Appearance of ‘McIntosh’ apple stored for 166 days at 1°C. Fruit maintains an acceptable visual quality up to 148 or 166 days of storage, but fruit shows internal breakdown after transfer to 20°C for 2 days.

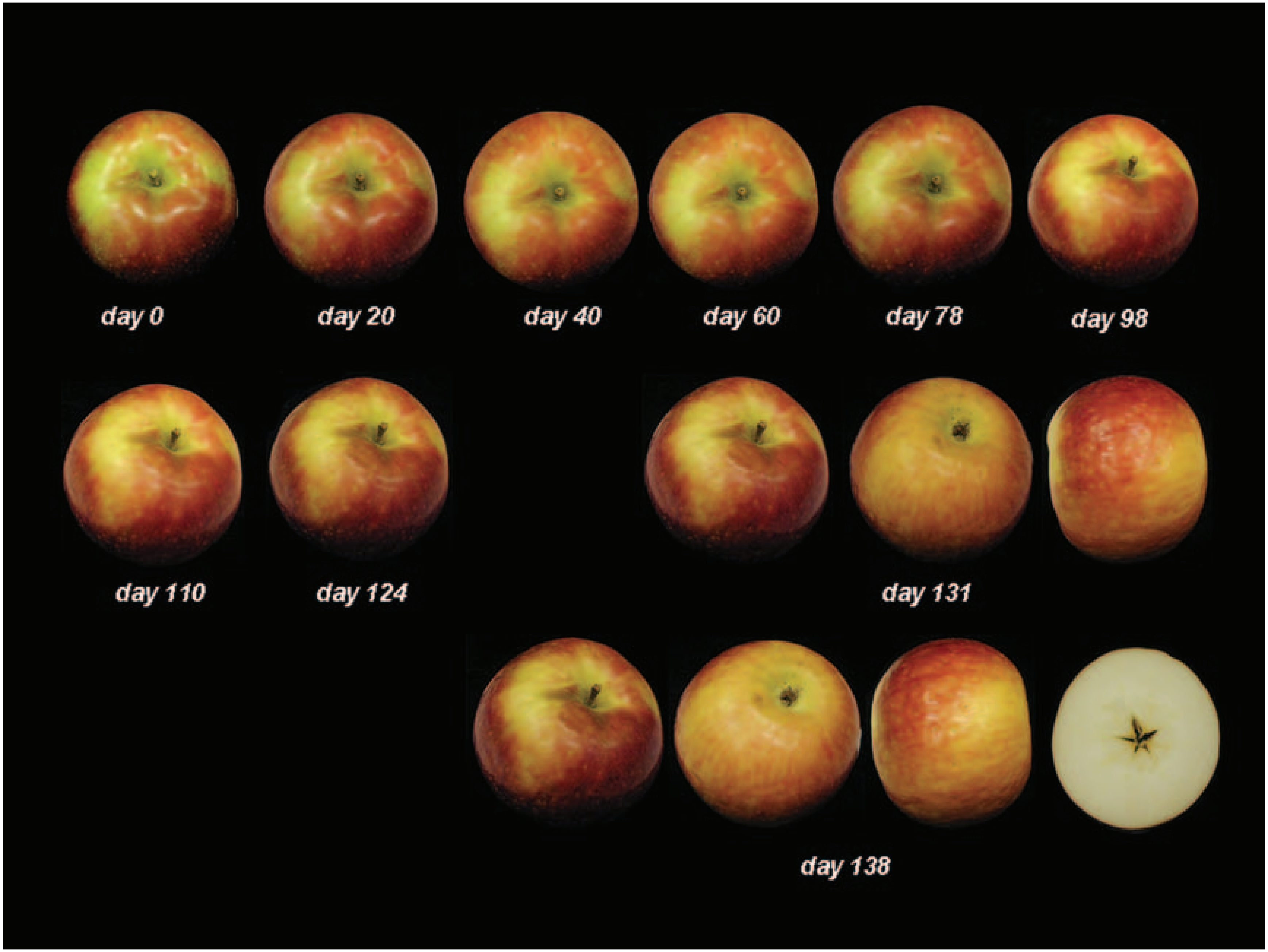
day 0
day 20
day 40
day 60
day 78
day 98
day 110
day 124
day 131
day 138

Figure 2.7. Appearance of 'McIntosh' apple stored for 138 days at 5°C. Fruit maintains an acceptable visual quality up to 124 days, but after 131 days skin shriveling is evident.

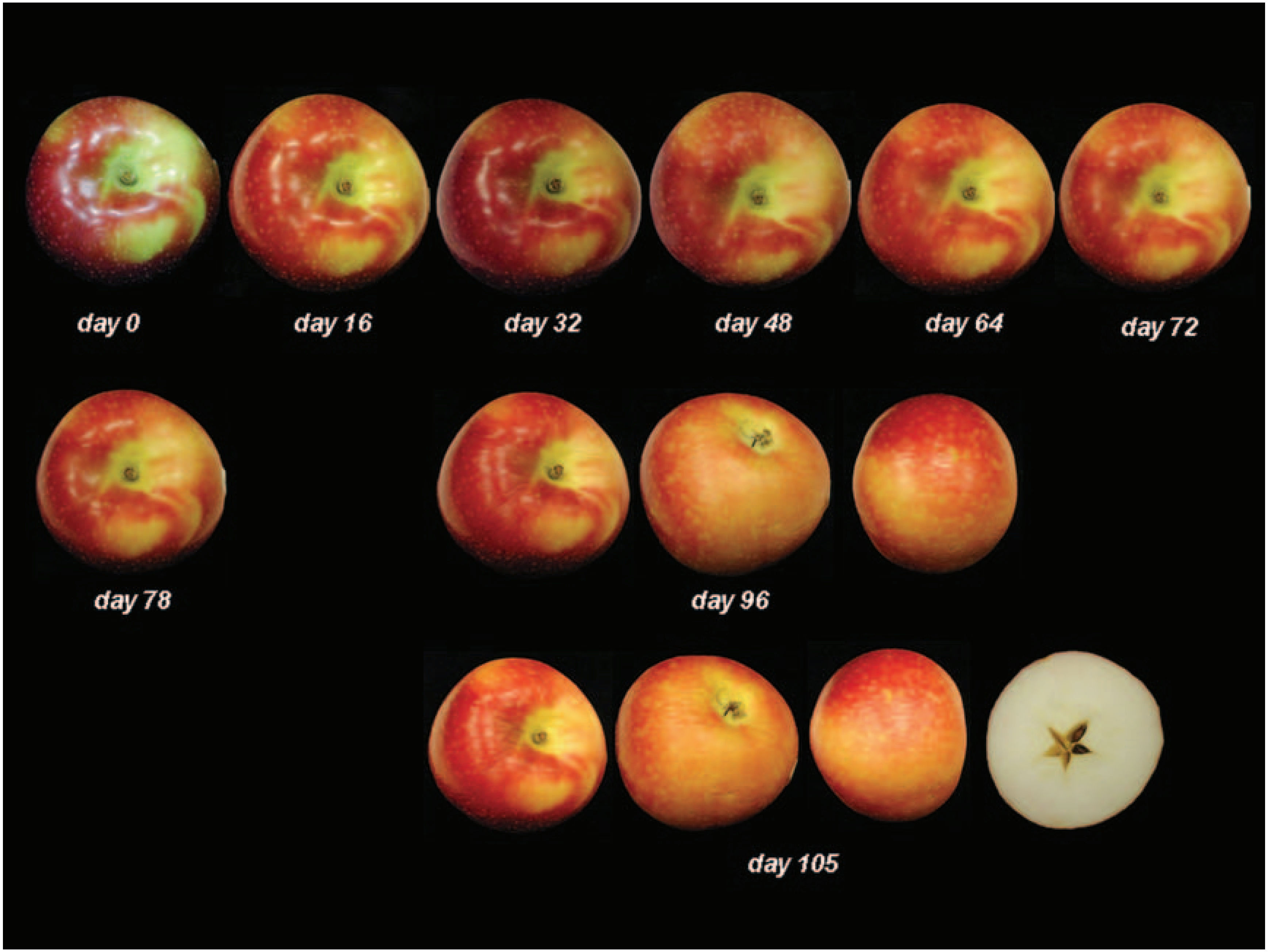
day 0
day 16
day 32
day 48
day 64
day 72
day 78
day 96
day 105

Figure 2.8. Appearance of ‘McIntosh’ apple stored for 105 days at 10°C. Fruit maintains an acceptable visual quality up to 78 days, but after 96 days skin shriveling is evident.

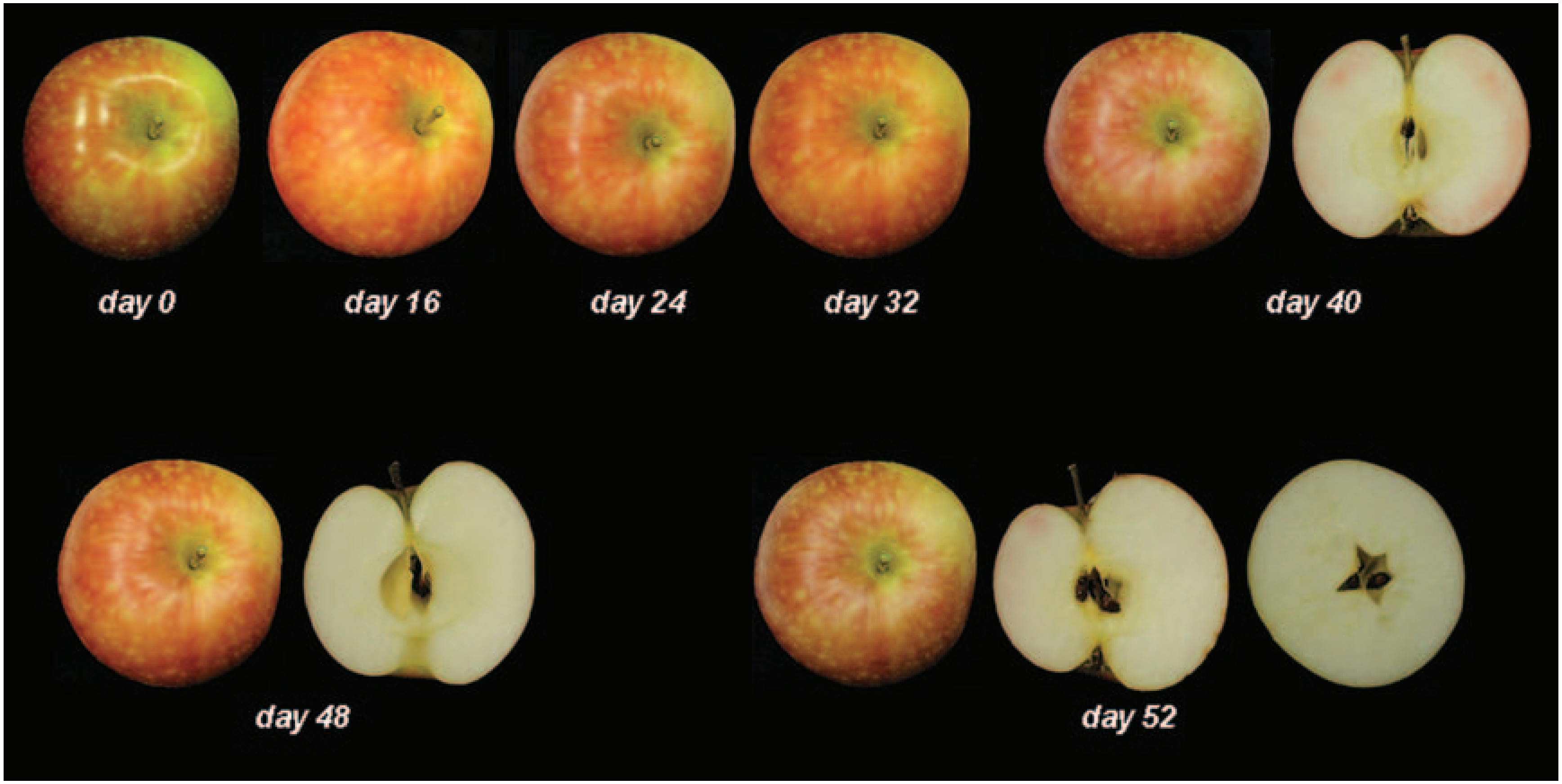
day 0
day 16
day 24
day 32
day 40
day 48
day 52

Figure 2.9. Appearance of 'McIntosh' apple stored for 52 days at 15°C. Fruit maintains an acceptable visual quality up to 32 days, but after 40 days skin shriveling is evident and fruit develops internal discoloration.

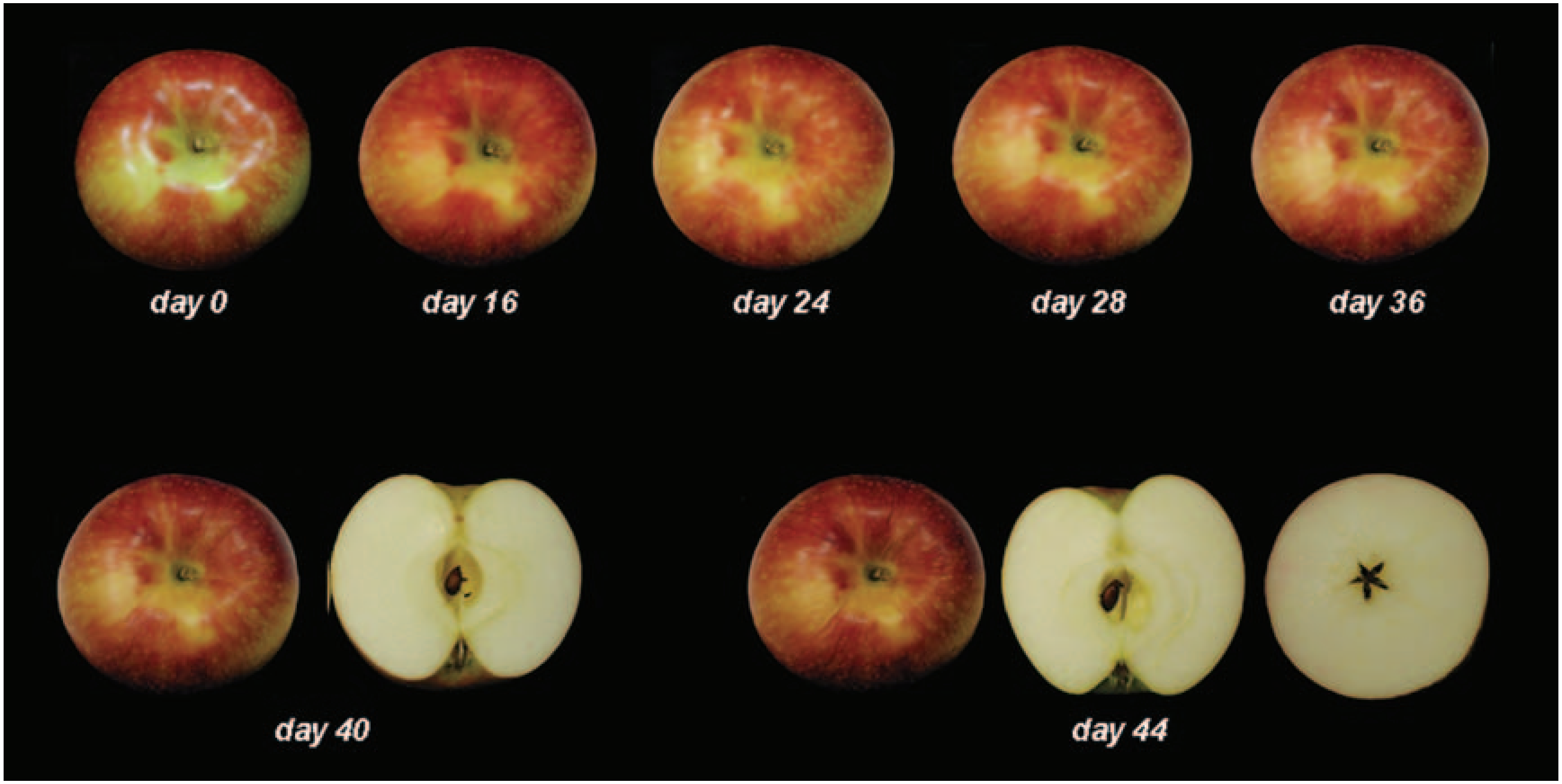
day 0
day 16
day 24
day 28
day 36
day 40
day 44

Figure 2.10. Appearance of ‘McIntosh’ apple stored for 44 days at 20°C. Fruit maintains an acceptable visual quality up to 28 days, but after 44 days the fruit appears extremely shriveled.

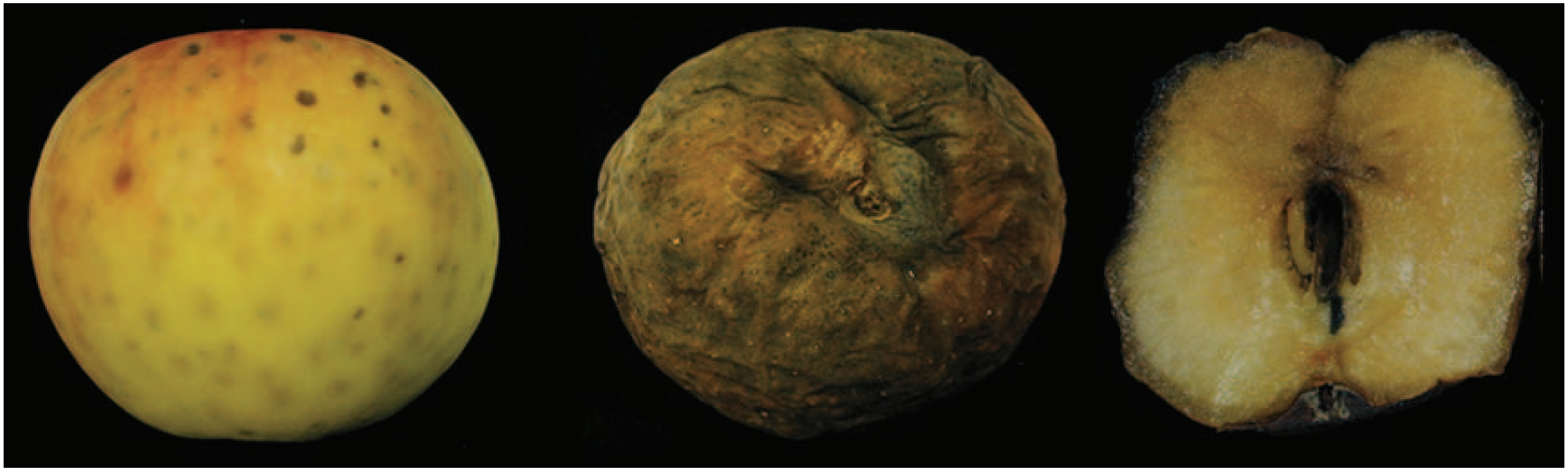

Figure 2.11. Bitter pit in ‘McIntosh’ apple stored for 40 days at 15°C (left); extreme decay and internal breakdown after 40 days at 20°C (center and right).

PEACH

Scientific Name: *Prunus persica*
Family: Rosaceae

Quality Characteristics

Skin color, texture, sugar and acid contents, and flavor of freshly harvested peaches are important quality attributes that determine the postharvest visual and eating quality, and these are greatly influenced by the maturity of the fruit at harvest (Meredith et al. 1989; Selli and Sansavini 1995). That is, peaches harvested immature are more prone to develop symptoms such as shriveling or internal breakdown, have an inferior taste, and overall quality is lower than when harvested ripe. Conversely, fruit harvested too ripe may soften very fast and have a short postharvest life.

Several authors agree that skin ground color is one of the best indicators to measure peach maturity at harvest (Brovelli et al. 1998; Delwiche 1987; Delwiche and Baumgardner 1983, 1985; Luchsinger and Walsh 1998; Meredith et al. 1989). The term "ground color" refers to the color of that part of the fruit surface that is not obscured by the red "blush"; development of the blush is related to light exposure rather than fruit maturation. Measurement of flesh firmness is recommended when the skin ground color is masked by full red color before maturity (Brovelli et al. 1998; Crisosto and Kader 2004; Delwiche 1987; Perkins-Veazie et al. 1999). Although peaches are ready to harvest when no more than 10% of the fruit ground color is green (Delwiche and Baumgardner 1985), the best quality is obtained if peaches are allowed to ripen on the tree. This happens because as peaches ripen, the pH and soluble solids content significantly increase, whereas acidity decreases (Brovelli et al. 1998; Lim and Romani 1964; Robertson et al. 1991), and owing to their lower sucrose and malic acid contents and higher citric acid content, less ripe peaches are more sour than riper fruit (Colaric et al. 2005; Génard et al. 1994; Robertson et al. 1992).

Variations in the composition of California peaches were reported for white and yellow-flesh peach cultivars harvested at the mature stage and ripened at 20°C for 5 days (Gil et al. 2002). Yellow-flesh cultivars had higher acid content, lower pH, and lower antioxidant capacity compared to white-flesh cultivars, whereas carotenoid content was much higher in yellow-flesh cultivars than in white-flesh cultivars. Soluble solids content of white- and yellow-flesh peaches ranged from 9.3 to 12.3% and from 10.9 to 12.9%, respectively. Acidity ranged from 0.13 to 0.31% in white-flesh cultivars and from 0.45 to 0.87% in yellow-flesh cultivars (Gil et al. 2002). Although yellow-flesh peaches were reported to have higher acidity levels, they lose 10–30% of their acidity during ripening, resulting in a fruit with increased sweetness (Crisosto et al. 2001). Fully ripe peaches have, in general, higher total sugar content, higher soluble solids content-to-acidity ratio, and lower acidity, and are thus sweeter than half-mature fruit (Robertson et al., 1991, 1992; Romani and Jennings 1971; Selli and Sansavini 1995). In addition, peaches with a soluble solids content of 14% or greater have a higher degree of acceptance by consumers (Crisosto and Crisosto 2005; Crisosto and Kader 2004; Crisosto et al. 2006).

As peach fruit ripens the volatile contents responsible for the aromatic flavor also increase, attaining maximum values in full ripe fruit. In fact, volatiles are produced in greater amounts by more mature than by less mature peaches, and at the ripe stage the more mature harvested peaches yield six times as many volatiles than less mature fruit (Lim and Romani 1964). The eating quality of peach fruit is not only dependent on the sugar-to-acid ratio but also on the content of aromatic compounds (Lim and Romani 1964; Selli and Sansavini 1995). The sugar-to-organic acid ratio and the levels of citric and shikimic acid have an important influence on perception of peach sweetness. Total organic acids, sucrose, sorbitol, and malic acid influence the aroma perception, whereas the malic-to-citric ratio, total sugars, sucrose, sorbitol, and malic acid affect the taste of peach fruit (Colaric et al. 2005; Robertson et al. 1991).

Peach fruit contains on average 88% water, 11% carbohydrates, 0.7% proteins, 2% fiber, 535 IU of vitamin A, and 7 mg of vitamin C per 100 g of fresh fruit (USDA 2006). Some peach genotypes are also notable for their particular functional properties, as they represent good sources of antioxidants other than vitamin C, such as total phenolics, anthocyanins, and carotenoids (Cevallos-Casals et al. 2006). In general, concentrations of phenolics, ascorbic acid, and β-carotene are higher in the peel of peach fruit than in the flesh, regardless of the cultivar. However, total phenolics and ascorbic acid contents are higher in white-flesh than in yellow-flesh peach cultivars (Gil at al. 2002). Total phenolics content ranged from 303 to 1,836 mg/kg in white-flesh peach cultivars and from 262 to 1,202 mg/kg in yellow-flesh cultivars. Total ascorbic acid content ranged from 48 to 202 mg/kg in white-flesh peach cultivars and from 31 to 181 mg/kg in yellow-flesh peaches. Conversely, β-carotene content was significantly higher (530–3,790 μg/kg) in yellow-flesh cultivars than in white-flesh cultivars (40–310 μg/kg) (Gil et al. 2002).

Optimum Postharvest Handling Conditions

Peaches are highly perishable, and if held for more than 2 or 3 weeks at or near 0°C may develop CI, which in peaches is also known as internal breakdown (IB). Interestingly, CI development is faster and more severe when peaches are stored at temperatures between 2 and 7°C than when they are stored at −1–0°C (Crisosto and Kader 2004; Lurie and Crisosto 2005). Susceptibility of peaches to CI not only depends on storage temperature but also on length of storage, type of cultivar, and maturity of the fruit at harvest (Crisosto et al. 1999; Feranández-Trujillo et al. 1998; Nunes and Emond 2002). For example, early harvested peach cultivars (May through June) are less susceptible to CI than are late-harvested cultivars (Crisosto et al. 1999). When stored at 2 or 5°C 'Dixieland' peaches developed symptoms of CI earlier than 'Flame Prince' peaches stored at the same temperature (Nunes and Emond 2002). In addition, the less mature the peach the higher the sensitivity to CI (Fernández-Trujillo et al. 1998). Chilling-damaged peaches may appear normal when removed from cold storage, but do not ripen satisfactorily and may develop internal injuries that are detected only at the consumer level. Peaches kept for more than 2 weeks at temperatures between 2 and 7°C may develop symptoms of CI, which are characterized by flesh browning, lack of juiciness (wooliness), dry and mealy texture, black pit cavity, flesh translucency, red pigment accumulation (bleeding), and loss of flavor (Lurie and Crisosto 2005). Therefore, to avoid severe development of CI, peaches should be maintained at temperatures between −1 and 0°C with a relative humidity of 90–95% (Crisosto and Kader 2004; Crisosto et al. 1999).

Compared to noncooled fruit, peaches exposed to temperatures lowered promptly after harvest by hydro-cooling or by forced-air cooling with high humidity cool air resulted in reduced bruising and weight loss of ripe fruit during subsequent storage at 4°C (Brusewitz et al. 1992). Although hydro-cooled fruit had less weight loss (0.2–0.4%) compared to fruit exposed to forced-air cooling (0.6–1.4%) or traditional room air cooling (0.7–1.6%), after 1 day of cooling, decay was higher in hydro-cooled (up to 22.8%) compared to forced-air cooled fruit (5.8%), probably because of the difficulty with water sanitation in hydro-cooling systems. Peaches that were air cooled at 1°C prior to ripening at 15 or 20°C for 10 days had less decay than noncooled fruit. In addition, cooling before ripening at 20°C resulted in the best peach flavor without excessive quality losses (Fernández-Trujillo et al. 2000). Prompt pre-cooling after harvest also delayed ripening of fruit after subsequent storage compared to traditional air pre-cooling (Tonini and Caccioni 1991).

Temperature Effects on Quality

Skin ground color is probably one of the best single indicators for measurement of peach postharvest ripening. Among the coordinates used to measure color, a* value seems to be the best indicator of color changes during ripening of peaches, whereas L* value, b* value, hue, and chroma change only slightly. As maturity increased, a* values of 'Dixieland' and 'Flame Prince' fruit increased, whereas L* and b* values did not change significantly (Nunes and Emond 2002). Meredith et al. (1989) also reported that changes in a* and hue values showed that ground color of peaches changed from green to yellow and then to red as maturity increased. In addition, external hue tended to decrease during storage of peaches at 8°C, indicating an increase in red and orange pigments (Karakurt et al. 2000). L* value of fruit stored at 12, 15, or 20°C decreased, meaning that the skin color changed from a lighter to a darker color. Hue and chroma values did not change much with time, regardless of the storage temperature, whereas a* values increased significantly, particularly in 'Dixieland' peaches. Changes in a* values suggest that the skin ground color of peaches changed during storage, and after 14–21 days, depending on the storage temperature, the peaches were completely ripe. Less ripe fruit showed a greater increase in a* values during storage, particularly fruit stored at 20°C, when compared to more mature fruit (Nunes and Emond 2002). As observed with other peach cultivars stored for 7 days at 5°C, slower color changes were observed during storage of 'Flame Prince' peaches at either 2 or 5°C, compared to higher storage temperatures (Nunes and Emond 2002; Shewfelt et al. 1987).

Changes in peach firmness are also considered an important indicator of fruit ripening during storage. In general, as temperature and storage time increase, firmness decreases, whereas the fruit ground color changes to a deeper, more uniform color. For example, as storage temperature increased from 15 to 20°C, firmness and skin hue of 'Marigold' peaches significantly decreased (Fernández-Trujillo et al. 2000). After approximately 2 days at 20°C, firmness of 'Dixieland' peaches was considered unacceptable, as the fruit was very soft to the touch (Nunes and Emond 2002). Several authors have correlated increases in a* value with the loss of firmness as peach fruit mature (Delwiche and Baumgardner 1983; Luchsinger and Walsh 1998; Meredith et al. 1989). For example, Luchsinger and Walsh (1998) studied several peach cultivars and reported that among the color variables studied, a* values showed the largest changes during maturation and presented the best correlation with firmness. Delwiche and Baumgardner (1983) reported that differences in ground color for various maturities occurred primarily in a* value and that firmness correlated most highly with a* value. In fact, regression analysis of 'Dixieland' and 'Flame Prince' a* values and firmness showed a very high correlation between these two maturity indicators ($r^2 = -0.99$). Therefore, as a* value increased, firmness of the fruit decreased, meaning that the peaches became more red, less firm, and more ripe during storage (Nunes and Emond 2002). Meredith et al. (1989) reported similarly that as the maturity of peaches increased, firmness decreased, but immature and threshold mature peaches never developed an acceptable firmness, even after 7 days at 27°C.

Visual symptoms of CI may develop within 1 or 2 weeks when peach fruit is stored between 2 and 5°C (Fernández-Trujillo et al. 1998; Lurie and Crisosto 2005). 'Paraguayo' peaches stored at 4°C developed symptoms of CI such as slight brown pits in the subepidermal tissues, and with increasing storage time the tissues became brown and dry and browning reached the pit cavity after 4 weeks of storage (Feranández-Trujillo et al. 1998). Lack of juiciness is often associated with mealiness, and hard or woolly texture is a common symptom in peaches exposed to chilling temperatures. Flesh textural changes are usually observed before the development of flesh browning in chilled peaches (Crisosto et al. 1999; Lurie and Crisosto 2005). Although IB reduced the quality of 'Flame Prince' peaches stored at 2 and 5°C, an unacceptable taste developed even before any signs of CI were evident. Consequently, after approximately 8 or 6 days at 2 or 5°C, respectively, the taste of 'Flame Prince' peaches was already objectionable, whereas visual symptoms of CI were only objectionable after 12–14 days at the same temperatures (Nunes and Emond 2002). Crisosto and Labavitch (2002) also reported that flavor of peaches was lost approximately 5 days prior to the appearance of visual symptoms of IB due to chilling damage. Furthermore, softening of 'Flame Prince' peaches stored at 5°C became objectionable after 15 days (Nunes and Emond 2002). In peaches of different maturities stored for 7 days at 5°C, loss of firmness ranged between 37 and 73% (Shewfelt et al. 1987). Overall, after approximately 18 days, quality of 'Flame Prince' peaches stored at 2°C was reduced owing to the development of objectionable taste, whereas after 12 days at 5°C the quality of the fruit was reduced by the development of CI symptoms combined with objectionable taste and fruit softening (Nunes and Emond 2002). No signs of CI developed in 'Flame Prince' peaches stored at temperatures higher than 5°C (Nunes and Emond 2002). However, in 'Fla 94–36' peaches stored at 8°C, wooliness symptoms such as internal reddish-brown discoloration, granular texture, and lack of juiciness developed in 50% of the fruit (Karakurt et al. 2000).

Holding 'Miraflores' peaches at 15°C delayed fungal development and reduced total fruit losses when compared to storage at 20°C. In addition, after 7 days of storage, off-flavors in peaches ripened at 20°C were higher compared to fruit ripened at 15°C, most likely due to advanced ripeness and fruit senescence (Fernández-Trujillo et al. 2000). After 14 days the fruit was completely soft, leaky, and decayed. As the storage period was gradually prolonged, the incidence of rot increased in peaches stored at 22–25°C (Tonini and Tura 1996).

Heat treatments, such as those suggested for quarantine insect disinfestation treatments, can be detrimental to the quality of peaches by accelerating and enhancing the development of mealiness. In fact, high-temperature forced-air treatment (temperature rapidly increased to 35°C and then linearly ramped up to 48.5°C over a period of 200 minutes) applied to peaches for 4 hours resulted in accelerated development of mealiness during subsequent storage at 5°C for 1 or 2 weeks (Obenland and Carroll 2000). Exposure of peaches to hot air or hot water at 46°C resulted in heat injury, whereas peaches heated by moist air at 37°C for 12 or 16 hours effectively maintained their firmness and had reduced water loss during subsequent storage at 2.3°C. In addition, heat-treated peaches were firmer than nonheated fruit stored continuously at 2.3°C (Zhou et al. 2002).

Weight loss of peaches owing to loss of moisture is also an important factor that determines the quality of the fruit. Loss of moisture during storage results in a peach with a shriveled and dry appearance, and the symptoms are aggravated with increasing the storage time and temperature. For example, shriveling increased with storage time in fruit stored at 12, 15, or 20°C but was negligible in fruit stored at 2 or 5°C. 'Dixieland' peaches stored at 12 or 15°C reached a moderate shriveling level after approximately 12 days, whereas 'Flame Prince' peaches stored at 12, 15, or 20°C reached moderate shriveling levels after 14, 15, and 10 days, respectively (Nunes and Emond 2002). Peaches stored at temperatures higher than 5°C showed the highest increase in weight loss compared to fruit stored at 0 or 5°C. Levels of humidity combined with temperature have a significant effect on the weight loss and appearance of peaches. For example, peaches stored at 6°C and 68% humidity had one and a half to three times greater weight loss than those stored at 4°C and 93% humidity, whereas peaches stored at 23°C and 50–60% humidity showed the highest rate of weight loss per day (2.5%) (Brusewitz et al. 1992). Storage at 20°C contributed to the highest weight loss in 'Flame Prince' and 'Dixieland' peaches (Nunes and Emond 2002). In peaches, the percentage weight loss associated with zero, trace, slight, moderate, severe, and extremely severe shriveling was less than 9, 11, 14, 16, 18, and 20%, respectively. Therefore, more than 16% weight loss (moderate shriveling) needed to be attained before the appearance of peaches was compromised (Hruschka 1977). 'Flame Prince' and 'Dixieland' peaches stored at 0 or 5°C never reached such high weight loss values during 21 days of storage, most likely because the humidity levels were maintained at around 95% (Nunes and Emond 2002). Peach fruit stored at 12, 15, or 20°C reached 16% weight loss after approximately 13, 12, and 9 days, respectively. Shriveling ratings at those same temperatures reached the "moderate" level between 13 and 19% weight loss. 'Dixieland' peaches stored at 12 or 15°C reached the moderate shriveling rating after approximately 12 days, which corresponded to a weight loss of 14 or 13%, respectively. 'Flame Prince' peaches showed higher weight loss for the same shriveling rating. Therefore, 'Flame Prince' peaches stored at 12, 15, or 20°C attained the moderate shriveling rating after 14, 15, and 10 days, which corresponded to weight losses of 17, 19, and 18%, respectively (Nunes and Emond 2002). It was also reported that, owing to moisture lost from peach fruit during storage at 5°C, the percentage extractable juice may decline by about 12–20% (Perkins-Veazie et al. 1999).

Peach chemical composition also changes during storage and is greatly influenced by handling temperatures (Crisosto et al. 2001; Meredith et al. 1989; Perkins-Veazie et al. 1999). Compared to storage at 15°C, storage of 'Marigold' peaches for 10 days at 20°C resulted in decreased soluble solids content, pH, and sugar-to-acid ratio, and increased acidity (Fernández-Trujillo et al. 2000). However, peaches ripened for 7 days at 21°C showed a decrease in acid concentrations and an increase in the sugar-to-acid ratio and contents of sucrose and flavor volatiles. The decrease in acidity and increase in sucrose concentration contributed to a peach with better sensory acceptability (Meredith et al. 1989). In 'Majestic' peaches stored at 5°C for 1 to 4 weeks, the soluble solids content-to-acidity ratio increased with storage time and was highest in fully ripe fruit compared to less ripe fruit (Perkins-Veazie et al. 1999). The phenolic content and the pH also increased during storage of peaches at 5°C, and as the total phenolics content increased, the susceptibility to flesh browning tended to increase (Cheng and Crisosto 1995; Perkins-Veazie et al. 1999).

Time and Temperature Effects on the Visual Quality of Flame Prince Peaches

Flame Prince peaches shown in Figures 2.12–2.19 were harvested at tree-ripe maturity of approximately chip five (Meredith et al. 1989), skin ground color L* = 66, a* = 8.4, and hue = 77.8 from a commercial operation in Fort Valley, Georgia, during the summer season (i.e., July–August). Promptly after harvest, fresh peach fruit was stored at five different temperatures (2.0 ± 0.3°C, 5.0 ± 0.2°C, 9.4 ± 0.4°C, 14.40 ± 0.4°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Flame Prince peaches stored at 2°C maintain acceptable appearance for up to 20 days. The orange color of the fruit deepens during storage and changes from a light reddish-orange to a deeper orange color (Figure 2.12). Flame Prince fruit held for 16 days at 2°C and then transferred to 20°C for 2 additional days develops symptoms of CI, which reach severe levels after approximately 20 days of storage at 2°C plus 2 additional days at 20°C. Nonvisual symptoms of CI such as mealiness and wooliness (lack of juiciness) develop simultaneously with flesh translucency, internal reddening (radiating from the pit), and tissue browning (Figure 2.13).

Peach fruit stored at 5°C maintains an acceptable visual quality for up to 21 days. After 6 days the color of the fruit changes from a greenish-orange to a light orange (Figure 2.14). Upon transfer to 20°C for 2 days, symptoms of IB develop in Flame Prince peaches stored at 5°C for approximately 18 days, and the symptoms are more severe than in peaches stored at 2°C. Juice exudate, mealiness, internal browning, reddening of the flesh, browning of the pit cavity, and decay are evident in peaches held for 18 or 21 days at 5°C plus 2 additional days at 20°C (Figure 2.15).

Peaches stored at 12°C maintain acceptable visual quality for up to 14 days. After that, shriveling becomes visible and the appearance of the fruit deteriorates. Peach skin color changes during storage, and after 20 days the fruit surface color is practically fully red with only very slight traces of yellow. Internal appearance of the fruit remains acceptable for up to 8 days of storage at 12°C, but after 10 days some juice exudes from the flesh adjacent to the skin (Figure 2.16).

Color of Flame Prince peach fruit changes rapidly at 15°C, and after 6 days the fruit develops a deeper orange color, which becomes even darker after 16 days. After approximately 14 days, signs of shriveling are evident, and after 16 days a slight browning develops near the stem-end of the fruit. Internal quality of the fruit is still acceptable after 10 days of storage. After 16 days, the fruit appears soft, shriveled, and overripe. Therefore, peaches stored at 15°C maintain an acceptable external appearance for up to approximately 10–12 days (Figure 2.17).

Visual quality changes occur rapidly when peaches are held at 20°C. Ground color changes very quickly from a light reddish-orange to a darker orangish-red color. The fruit maintains acceptable visual quality for up to 8 days, but after 12 days the fruit appears overripe. Development of decay, internal browning, and juice exudate are evident after 14 days, and the quality of the fruit deteriorates rapidly (Figure 2.18). Decay at the stem-end of the fruit, softening of the tissues, and browning develop in peaches stored for 10 days at 20°C, and after 14 days browning of the internal tissues adjacent to the skin attains severe levels (Figure 2.19).

Overall, changes in the visual quality of Flame Prince fruit occur faster and are more severe as time and storage temperature increase. At temperatures lower than 10°C, IB as a result of chilling damage reduces the quality of the fruit, whereas at higher temperatures, shriveling, decay, overripe appearance, and internal browning are the major visual changes that limit fruit quality. Flame Prince peaches maintain better external quality for longer periods when stored at 2 or 5°C (20–21 days, respectively), but IB develops when the fruit is stored for more than 2 weeks at these temperatures. Visual quality of Flame Prince peaches stored at 10, 15, or 20°C remains acceptable for 14, 12, and 8 days, respectively, but deteriorates quickly afterward.

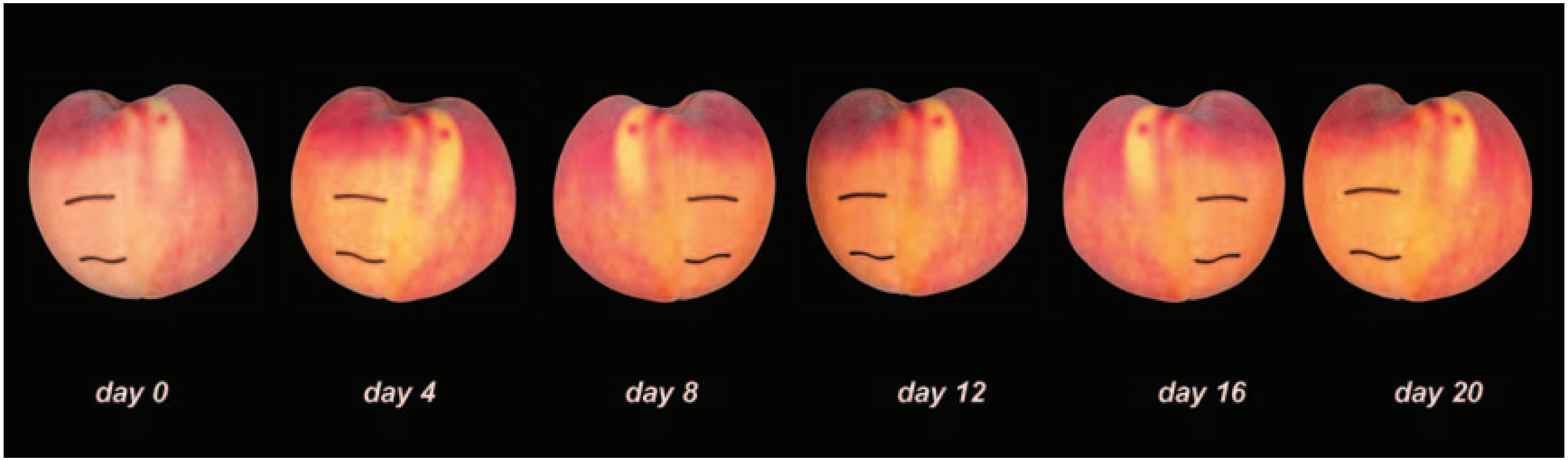
day 0
day 4
day 8
day 12
day 16
day 20

Figure 2.12. Appearance of ‘Flame Prince’ peach stored for 20 days at 2°C. Ground color changes slightly from a light orangish-red to a deeper orangish-red but the fruit maintains an acceptable visual quality up to 20 days of storage.

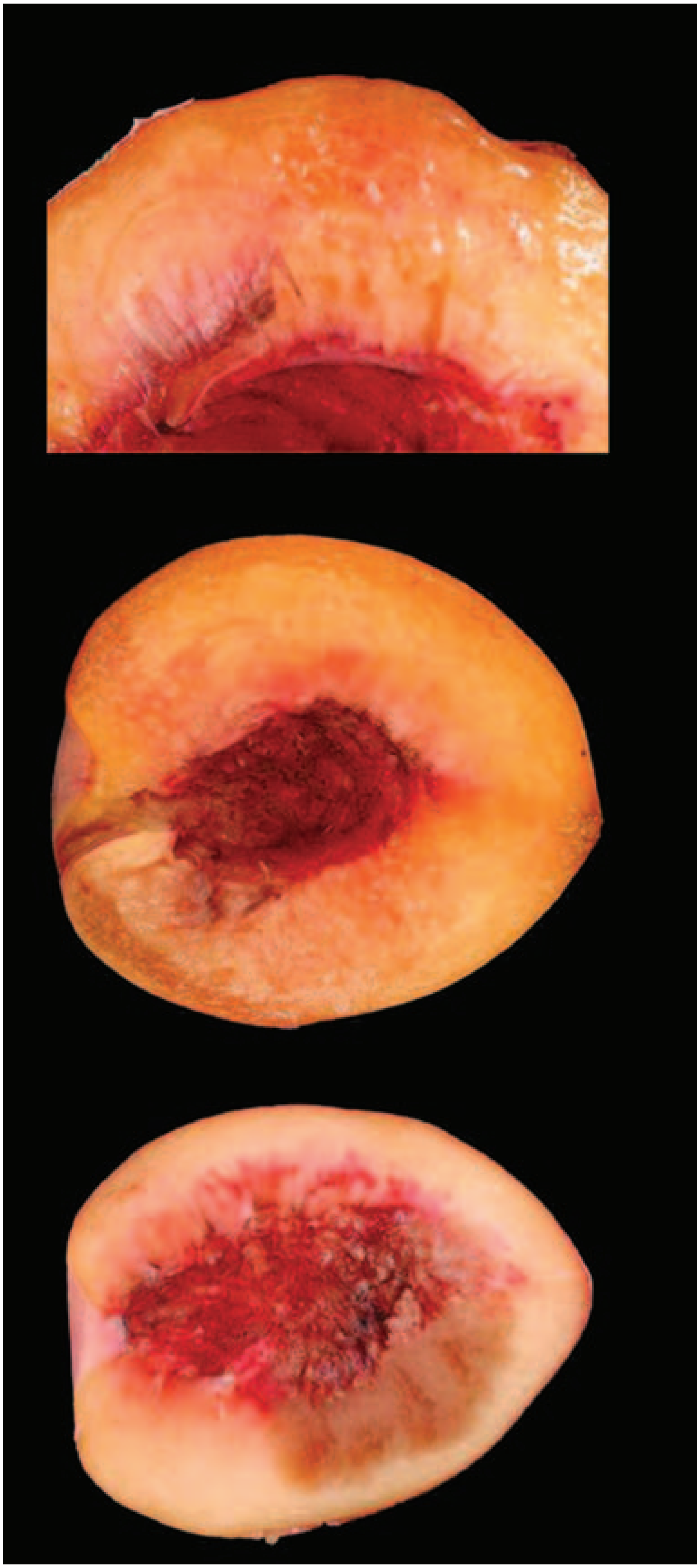

Figure 2.13. Chilling injury symptoms: mealiness and wooliness, internal browning, and internal reddening in 'Flame Prince' peach following storage for 16 days (right and center) and 20 days (left) at 2°C plus transfer for 2 days at 20°C.

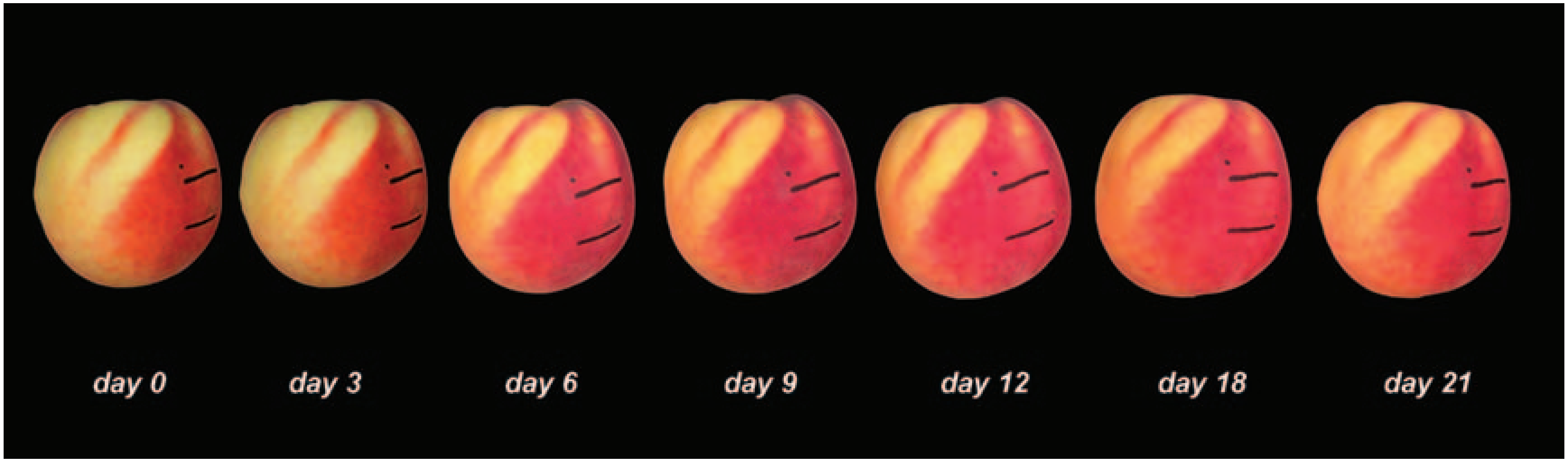
day 0
day 3
day 6
day 9
day 12
day 18
day 21

Figure 2.14. Appearance of 'Flame Prince' peach stored for 21 days at 5°C. Ground color changes slightly from a light orangish-red to a deeper orangish-red, but the fruit maintains an acceptable visual quality up to 21 days of storage.

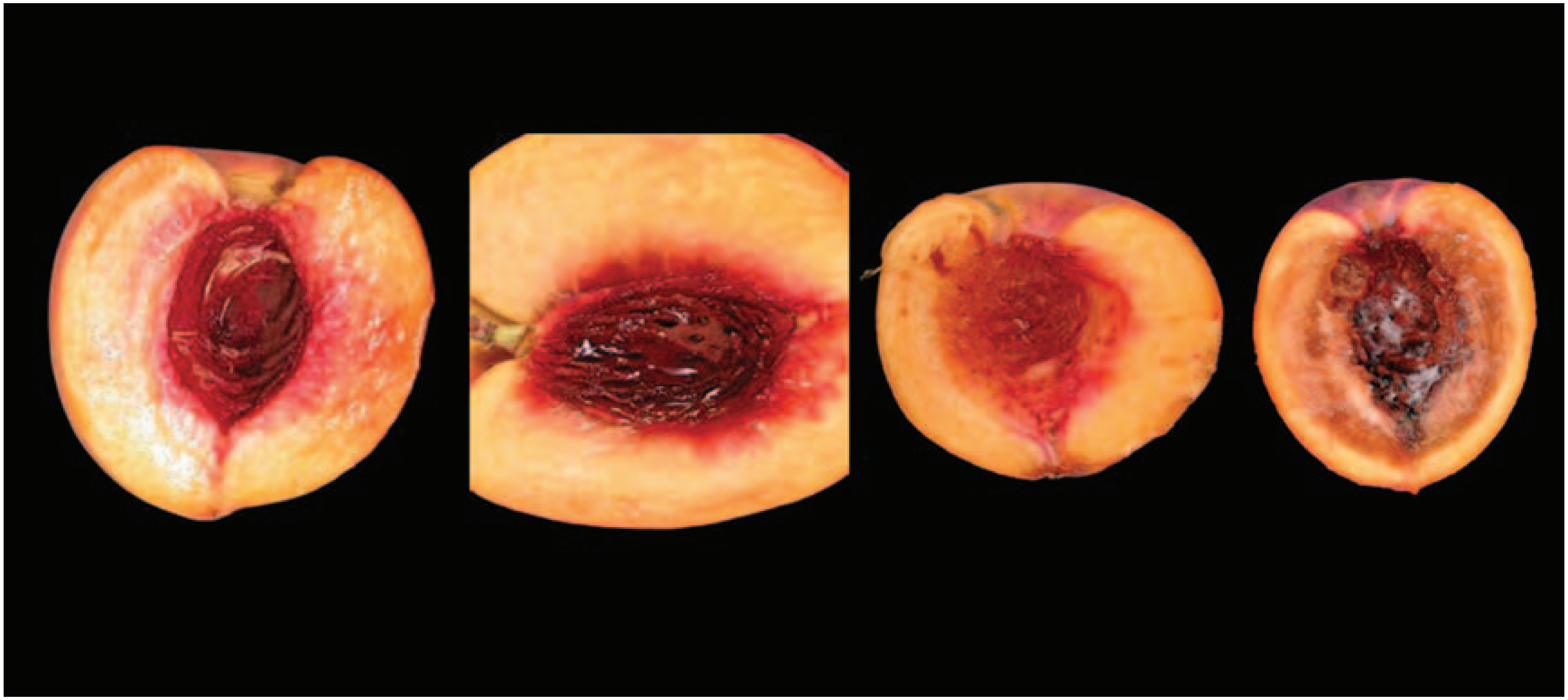

Figure 2.15. Chilling injury symptoms: juice exudate, mealiness, internal browning, reddening of the flesh, browning of the pit cavity, and decay in 'Flame Prince' peach after storage for 18 days (right and center right) and 21 days (center left and left) at 5°C plus transfer for 2 days at 20°C.

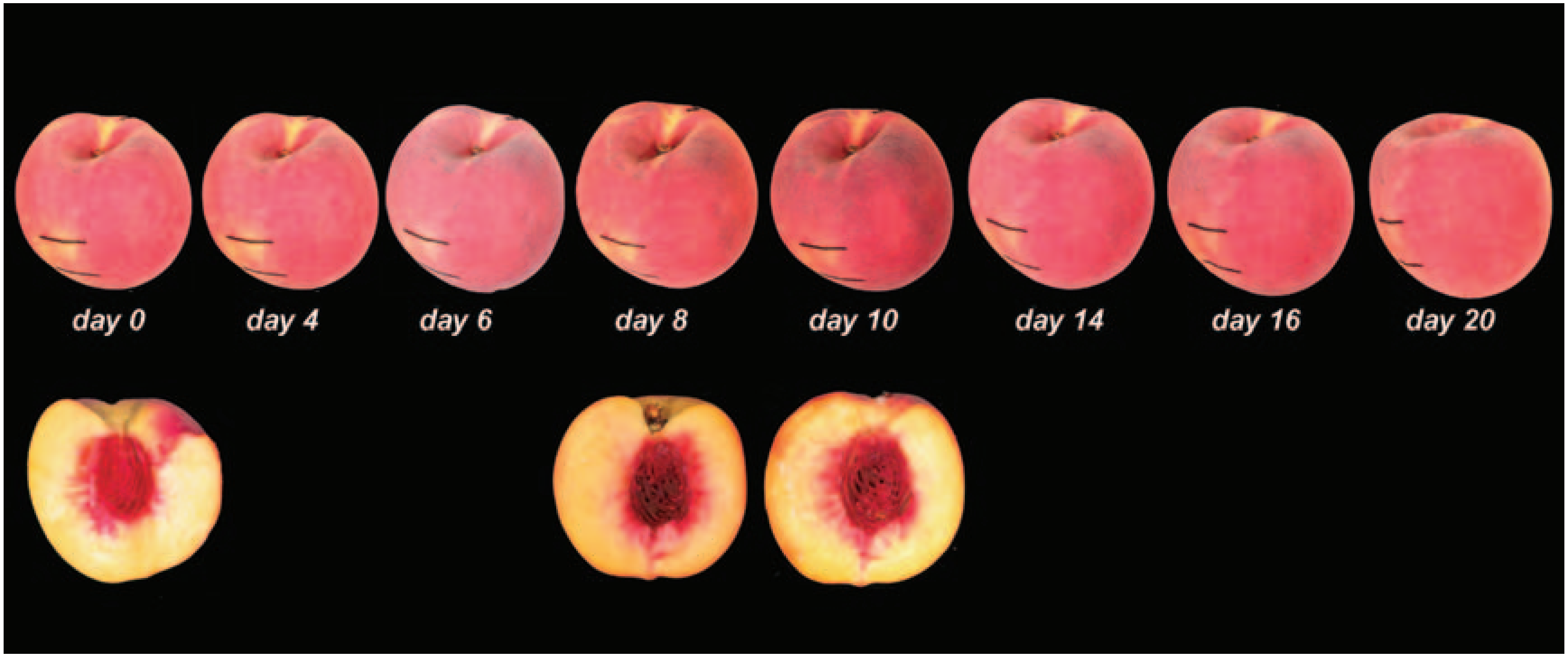
day 0
day 4
day 6
day 8
day 10
day 14
day 16
day 20

Figure 2.16. Appearance of 'Flame Prince' peach stored for 20 days at 12°C. The fruit maintains an acceptable appearance up to 14 days of storage, but then appears slightly shriveled.

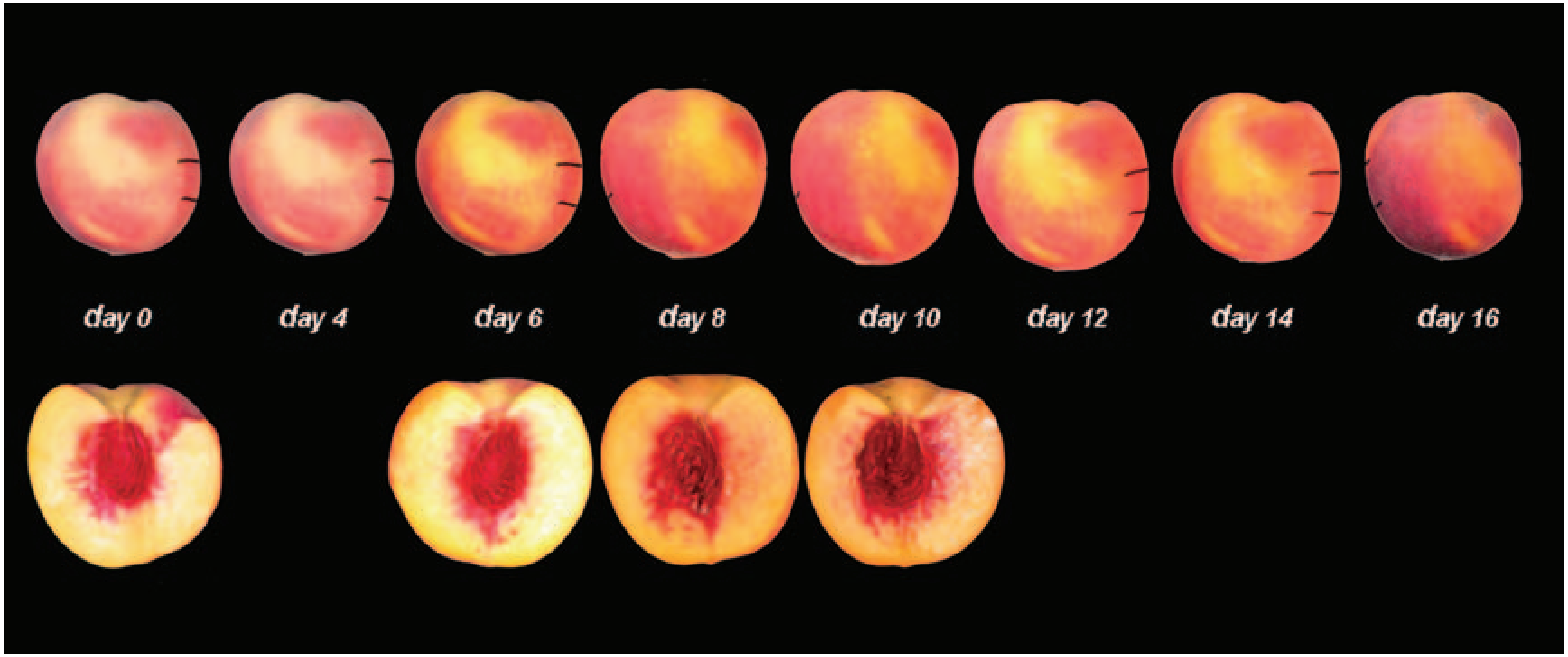
day 0
day 4
day 6
day 8
day 10
day 12
day 14
day 16

Figure 2.17. Appearance of ‘Flame Prince’ peach stored for 16 days at 15°C. Ground color changes slightly from a light orangish-red to a deeper orangish-red. The fruit maintains an acceptable visual quality up to 14 days of storage, but after 16 days appears overripe.

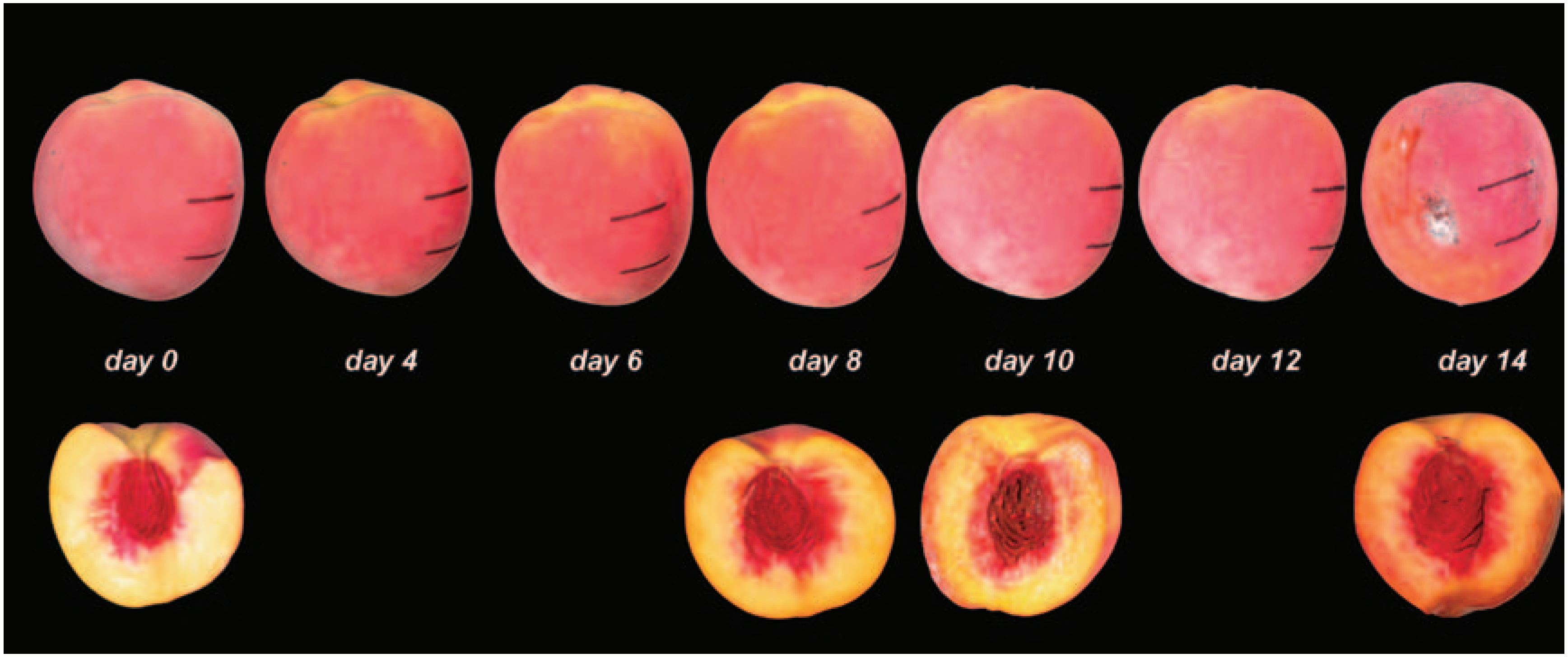

Figure 2.18. Appearance of 'Flame Prince' peach stored for 14 days at 20°C. Ground color changes from a light orangish-red to a deeper orangish-red. The fruit maintains an acceptable visual quality up to 8 days of storage, but after 12 days the fruit appears overripe. Development of decay and internal browning are evident after 14 days.

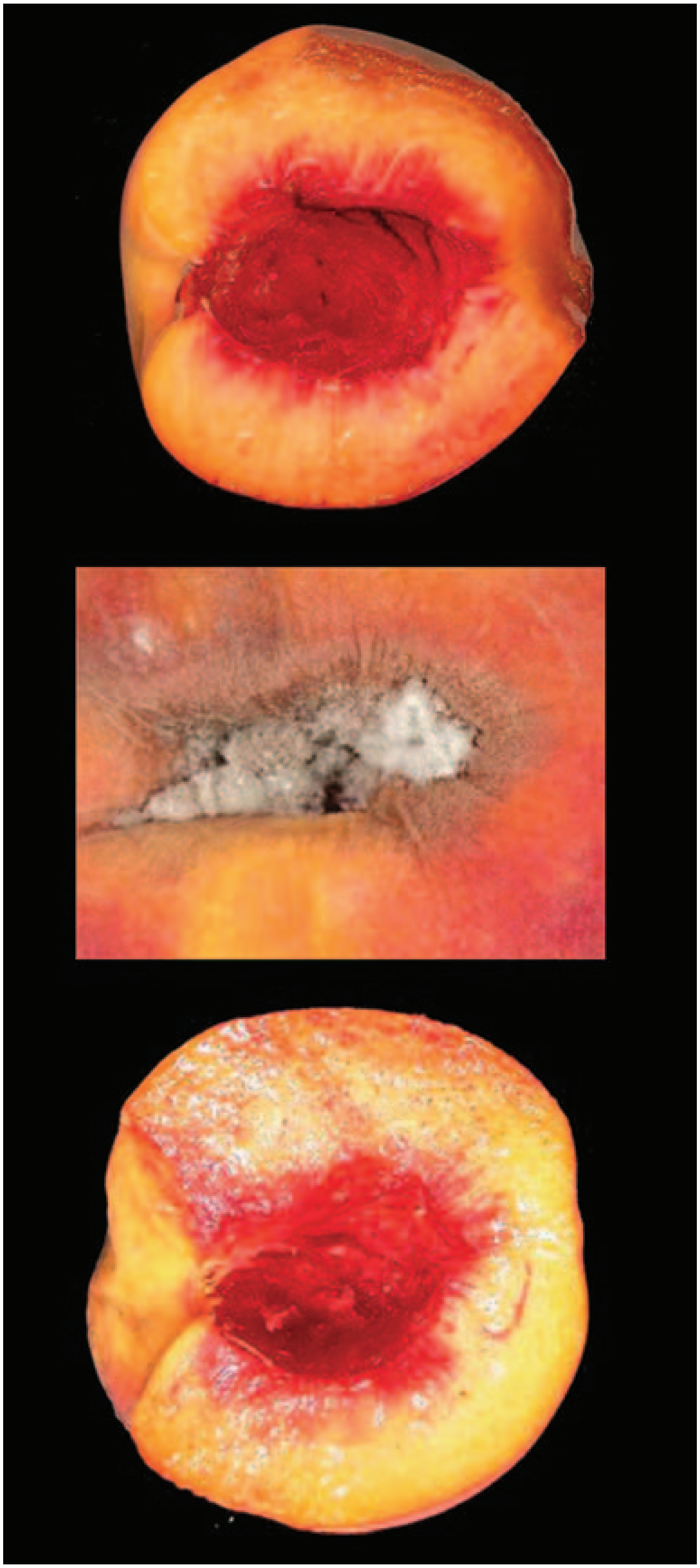

Figure 2.19. Temperature-related disorders (decay, softening, and browning) in ‘Flame Prince’ peach stored for 10 days (right and center) and 14 days (left) at 20°C.

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CHAPTER 3

SOFT FRUITS AND BERRIES

Blackberry
Blueberry
Currant
Raspberry
Strawberry
Bibliography

Color Atlas of Postharvest Quality of Fruits and Vegetables Maria Cecilia do Nascimento Nunes

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BLACKBERRY

Scientific Name: *Rubus* spp.
Family: Rosaceae

Quality Characteristics

Blackberries are widely grown in Asia, Europe, and North and South America. However, blackberries grown in specific regions of the world result mainly from species native to that region. The blackberry is a fruit formed by the aggregation of several smaller fruits, called drupelets. The drupelets are all attached to a receptacle, which is the fibrous central core of the fruit that may be greenish-white or purple. Unlike raspberries, where the receptacle separates from the berry and leaves a hollow core, the drupelets of blackberries remain attached to the receptacle, with the receptacle abscising from the plant during harvest. Blackberries are red to brown-red; are hard when they are immature; and turn black, shiny, and soft when they ripen. The ripe fruit is soft and juicy and has a very dark-purplish color with a smooth, fragile skin (Perkins-Veazie 2004). Because eating quality does not improve after harvest, blackberries should be harvested at the shiny-black stage, when the fruit attains a glossy fully black color, appears and feels turgid, and is easily detached from the plant (Mitcham et al. 2006; Perkins-Veazie et al. 1993b). When harvested, partially colored, blackberries are fairly astringent owing to their high acid and phenolic content. Although the preferable color for fresh market is glossy black (Daubeny 1996), some cultivars retain acidity and astringency well into ripeness and should be harvested at the dull-black color stage so they will be edible (Perkins-Veazie 2006a).

Blackberry cultivars also vary in texture and composition. For example, 'Navaho' blackberries are firmer, have a tougher skin, and are similar to 'Shawnee' in color and anthocyanin content. 'Arapaho' blackberries are lower in anthocyanin content than 'Cheyenne,' 'Shawnee,' or 'Choctaw' cultivars, and consequently were considered by some to be the most suitable cultivar for the fresh market (Clark and Moore 1990; Perkins-Veazie et al. 1993a, 1997). 'Thornfree,' 'Loch Ness,' and 'Chester Thornless' were considered the most important semi-erect types of raspberry cultivars produced worldwide, whereas 'Brazos' and 'Marion' were the most common erect and trailing types. Erect and semi-erect raspberry cultivars are usually grown for fresh marker and trailing cultivars for processing (Strik et al. 2007).

Overall, fruit quality attributes such as good flavor and color, optimum soluble solids and acidity combined with firm fruit texture and good skin strength, and good drupelets coherence and resistance to decay are the best requirements for a good quality blackberry with an extended postharvest life (Daubeny 1996).

Soluble solids and total sugar contents, pH, and volatile production increase from the red unripe to the dull-black overripe stages, whereas acidity decreases sharply as blackberries ripen (Perkins-Veazie et al. 2000a; Siriwoharn et al. 2004). Changes in acidity during blackberry ripening are, however, more accentuated than changes in the soluble solids content of the fruit. Depending on the cultivar, soluble solids content increased from approximately 4–15.7% until the black color stage, and then increased to approximately 10–18% between the ripe and dull-black stages, whereas acidity decreased from approximately 2–3% in unripe fruit to 1% or less in shiny-black stages (Pantelidis et al. 2006; Perkins-Veazie et al. 2000; Reyes-Carmona et al. 2005; Siriwoharn et al. 2004; Stanisavljevié 1999). Total sugar content increased from 200 μ/g fruit dry weight in red fruit to 600 μ/g fruit dry weight in black fruit (Perkins-Veazie et al. 2000). In general, blackberries contain about 5–6% total sugars, of which 1–5% is sucrose, 44–48% is glucose, and 47–49% is fructose (Perkins-Veazie et al. 1999a,1999b).

Anthocyanins, mainly cyanidin-3-glucoside, are first detected in green-red fruit, with the greatest increase in content occurring between the mottled and shiny-black stages of ripeness (Fan-Chiang and Wrolstad 2005; Perkins-Veazie et al. 2000). Anthocyanin content of blackberries is highly correlated with the color of the fruit, and the higher the anthocyanin content the deeper the color of the fruit (Perkins-Veazie et al. 1993a). Depending on the blackberry cultivar and maturity stage at harvest, as the fruit ripens, anthocyanin content significantly increased from 69.9 or 74.7 mg per 100 g in unripe fruit to 164 or 317 mg per 100 g fruit fresh weight in overripe fruit (Siriwoharn et al. 2004). At the ripe stage, the anthocyanin content of 'Chester Thornless,' 'Hull Thornless,' and 'Triple Crown' blackberry cultivars was 153.3, 171.6, and 133.5 mg cyanidin-3-glucoside per 100 g fruit fresh weight, respectively (Wang and Lin 2000). Besides cultivar variations and maturity of the fruit, anthocyanin content of blackberries also varies depending on the season of harvest and production area (Clark et al. 2002; Connor et al. 2005a; Fan-Chiang and Wrolstad 2005; Naumann and Wittenburg 1980; Pantelidis et al. 2006; Perkins-Veazie et al. 1993a; Reyes-Carmona et al. 2005). For example, anthocyanin content of blackberries grown in New Zealand ranged from 66.0 to 167.8 mg per 100 g fruit, whereas the anthocyanin content of blackberries grown in the United States ranged from 58.3 to 363.1 mg per 100 g fruit (Clark et al. 2002; Connor et al. 2005a; Fan-Chiang and Wrolstad 2005; Perkins-Veazie et al. 1993a;). Other different blackberry species grown in France, Chile, Greece, and Mexico contained on average 143.0, 141.5, 139.8, and 70.3 mg of total anthocyanin per 100 g of fruit, respectively (Fan-Chiang and Wrolstad 2005; Pantelidis et al. 2006). Total phenolic content of blackberries also varies depending on the species, cultivar, fruit maturity, season, and area of production. Total phenolic content did not increase much during ripening from the unripe to ripe stage (975–903 mg per 100 g fruit fresh weight), but a significant increase was observed from the ripe to the overripe stage (903–1,541 mg per 100 g fruit fresh weight) (Siriwoharn et al. 2004). Total phenolic content of blackberries grown in New Zealand and the United States ranged from 292.2 to 1,058.1 mg per 100 g fruit, respectively (Cho et al. 2005; Clark et al. 2002; Connor et al. 2005a). Depending on the cultivar, blackberries grown in Greece had a total phenolic content that ranged from 1,703 to 2,349 mg per 100 g fruit fresh weight (Pantelidis et al. 2006).

Because of their generous content of anthocyanins and phenolic contents in addition to other antioxidant compounds, blackberries are ranked among the fruits with the highest antioxidant capacity. However, like anthocyanin and phenolic contents, antioxidant capacity (defined as oxygen radical absorption capacity or as ferric-reducing antioxidant power) of the fruit also varies depending of the cultivar and maturity of the fruit, environmental conditions during growth, season of harvest, and production area (Connor et al. 2005a, 2005b; Pantelidis et al. 2006; Reyes-Carmona et al. 2005; Siriwoharn et al. 2004; Wang and Lin 2000). For example, antioxidant activity of blackberries grown in New Zealand ranged from 56.6 to 66.3 μmol/g fruit, whereas antioxidant activity content of blackberries grown in the United States ranged from 65.5 to 71.8 μmol/g fruit (Connor et al. 2005a, 2005b). Antioxidant activity increases as the fruit ripens and attains a maximum in the overripe stage (Siriwoharn et al. 2004). Blackberry fruit contains on average 88% water, 9.6% carbohydrates, 1.4% proteins, and 5% fiber (USDA 2006), 11–28 mg of vitamin C, and minor amounts of other vitamins per 100 g of fresh fruit (Agar et al. 1997; Hansen and Waldo 1944; Pantelidis et al. 2006; USDA 2006).

Optimum Postharvest Handling Conditions

To obtain the maximum postharvest life, blackberries should be promptly cooled within 4 hours after harvest to 5°C. Subsequently they should be stored as close as possible to 0°C and with 90–95% relative humidity. Under such conditions a postharvest life of 5–14 days is expected (Mitcham et al. 2006; Perkins-Veazie 2004a).

Temperature Effects on Quality

The rapid loss of blackberry quality after harvest contributes to the limited availability or to the poor quality of the fruit in the fresh market. Because of the lack of suitable cooling facilities and sometimes lack of knowledge about fruit requirements, blackberries are often handled under inadequate temperatures that may be as high as 10°C (Perkins-Veazie et al. 1999a). Exposure to temperatures above 0°C results in a rapid loss of fruit quality such as undesirable color changes, softening, shriveling, and compositional changes, and thus decreased acceptability for sale. When stored continuously at 2°C, blackberry maximum storage life was about 10 days for 'Navaho,' 7 days for 'Arapaho,' and 4 days for 'Choctaw' and 'Shawnee' blackberries. Holding blackberries at 5°C reduced the storage life to 5, 3, and 2 days for 'Navaho,' 'Arapaho,' and 'Choctaw' and 'Shawnee,' respectively. This represents half the storage life at 2°C (Perkins-Veazie et al. 1999a).

In general, the severity and incidence of decay in blackberries increases as the temperature and length of storage increases. For example, the percentage of decayed fruit after 7 days at 5°C was at least two times higher than in fruit stored for 7 days at 2°C, and the percentage of decayed fruit held 7 days at 10°C was three times higher than that of fruit held at 5°C for the same period (Perkins-Veazie et al. 1999a). After 7 days of storage, 4, 7, and 29% of 'Shawnee' blackberries were decayed after storage at 2, 5, or 10°C, respectively. Blackberries stored for 21 days at 2°C were less decayed (approximately 9%) than fruit stored for 7 days at 10°C (approximately 13%) (Perkins-Veazie et al. 1999a). Likewise, the percentage of leaky fruit increases with storage time and temperature. After 21 days at 2°C, 14 days at 5°C, and 7 days at 10°C, approximately 50% of the fruit was leaky and 33–36% of the fruit was unmarketable (Perkins-Veazie et al. 1999a). *Botrytis cinerea* was the main cause of infection in 20% of the blackberry fruit stored for 12 days at 2°C, whereas *Rhizopus stolonifer* caused some decay in the scar area of the fruit (Barth et al. 1995). 'Navaho' blackberries stored or shipped for 4 days between −0.5 and 1°C, held for 7 days at 20°C upon arrival, and then transferred to 20°C for 2 additional days showed significantly higher decay (14 and 43%, respectively) when compared to fruit that was not transferred to higher temperature (6 and 2%, respectively) (Perkins-Veazie et al. 1997). Therefore, holding blackberries for only 1 or 2 days at 20°C resulted in increased growth of gray mold (Perkins-Veazie 2004a; Perkins-Veazie et al. 1997). Holding 'Marion' blackberries at 0 or 5°C delayed the development of mold for 7 days, whereas berries held at 10 or 25°C developed mold after 48 hours of storage. Mold incidence was 5% when the fruit was held at 0°C, but increased to 22 and 79% when fruit was stored at 10 and

20°C, respectively (Varseveld and Richardson 1980). Holding blackberries for 2 days at 20°C following storage at 2 or 5°C increased the incidence of decay in 'Navaho' and 'Shawnee' fruit. Thus, after 21 days at 2°C, 28–73% of the fruit transferred for 2 additional days at 20°C was decayed, whereas, depending on the cultivar, 68–95% and 14–66% of the fruit was leaky or soft, respectively (Perkins-Veazie et al. 1999b). Decay and percentage of leaky fruit increased during storage at 2°C, and after 14 days 20–33% of the fruit was decayed, whereas 39–50% of the fruit was leaky (Perkins-Veazie and Collins 2002). Leaky fruit results from pathological or physiological breakdown, or both, when the fruit drupelets begin to leak fluid to the exterior (Mitcham et al. 2006).

Blackberry firmness also decreases with increasing temperature and duration of storage. For example, the percentage of firm 'Shawnee' blackberries decreased during storage, regardless of the storage temperature, from 41.9 to 29.2% after 7 and 21 days at 2°C, respectively. However, decrease in the percentage of firm fruit was higher at 5 and 10°C than at 2°C (Perkins-Veazie et al. 1999a).

Blackberries are very vulnerable to water loss, which results in fruit shriveling and loss of gloss (Mitcham et al. 2006). However, no changes in the coloration of the fruit were reported during storage. In fact, changes in color were negligible when 'Navaho' blackberries were stored at 2°C for 2 weeks (Perkins-Veazie et al. 2000), and although hue angle of blackberries stored at 2°C increased after 2 days of storage, it decreased gradually by 12 days (Barth et al. 1995). Conversely, loss of moisture seems to have a significant effect on fruit shriveling and loss of gloss (Mitcham et al. 2006). Weight loss among different blackberry cultivars stored at 2°C ranged from 0.8 to 3.3% after 7 days and was influenced by cultivars and color stage (Perkins-Veazie et al. 1996). Higher temperatures, above the optimum recommended for blackberries, combined with extended storage periods result in higher weight losses as a result of loss of moisture from the fruit. For example, weight loss of blackberries stored at 2°C increased from approximately 2.5% after 7 days to 6% after 21 days, whereas blackberries stored at 5 and 10°C showed a reduction of approximately 3 and 4% on the initial weight after 7 days of storage (Perkins-Veazie et al. 1999a).

In blackberries grown in Brazil, initial weight of the fruit was reduced by 7.91% and 14.83% when stored for 12 days at 2 and 20°C, respectively (Antunes et al. 2003). After 3 and 7 days at 2°C, 'Navaho,' 'Choctaw,' 'Cheyenne,' and 'Shawnee' fruit lost on average 1.8 and 3% of their initial weight, respectively (Perkins-Veazie et al. 1993b). 'Chester' and 'Navaho' blackberries showed the highest weight loss reported, and after a 3-week storage period at 3 ± 2°C fruit had lost 22% and 49% of its initial weight, respectively (Basiouny 1995). 'Marion' blackberries stored for only 4 days at 10 and 20°C showed weight losses of 1.8 and 3.8%, respectively, whereas fruit stored for 10 days at 0°C reached only a maximum weight loss of 0.6% (Varseveld and Richardson 1980). 'Navaho' blackberries stored or shipped for 4 days at temperatures between −0.5 and 1°C, held for 7 days at 20°C upon arrival, and then transferred to 20°C for 2 additional days showed significantly higher weight loss (4.7 and 6.5%, respectively) when compared to fruit handled likewise but not transferred to 20°C (2.9 and 2.6%, respectively) (Perkins-Veazie et al. 1997). Holding blackberry fruit for 2 days at 20°C following storage at 2 or 5°C resulted in additional weight loss of 0.5% to 2.5%, respectively (Perkins-Veazie et al. 1999b).

Temperature has a major effect on the compositional changes of blackberries during storage. For example, soluble solids content of blackberries fluctuated, whereas acidity declined, and pH and soluble solids content-to-acidity ratio increased during storage at 2, 5, or 10°C. The desirable increase in soluble solids content-to-acidity ratio was most likely the result of a decrease in acidity rather than an increase in the soluble solids content of the fruit (Perkins-Veazie et al. 1999a, 1999b). Soluble solids and acid contents of 'Navaho' and 'Chester' blackberries declined during storage at 3 ± 2°C, resulting in fruits with unpleasant taste and unmarketable qualities after 3 weeks of storage (Basiouny 1995). A 53% reduction in the soluble solids content of blackberries was reported after storage for 12 days at 20°C, whereas no significant changes were observed in fruit stored continuously at 2°C (Antunes et al. 2003; Perkins-Veazie and Collins 2002). Total sugar content of blackberries stored at 2°C decreased by 22.6% during storage compared to initial values, and although sucrose and fructose contents declined slightly during storage, glucose content of the fruit increased (Perkins-Veazie et al. 1999a, 1999b).

Total ascorbic acid content of blackberries decreased from an initial value at harvest of about 80 mg to about 40 mg per 100 g fresh weight after 12 days of storage at 20°C, whereas fruit stored at 2°C lost 51% less ascorbic acid content compared to fruit stored at 20°C (Antunes et al. 2003).

Anthocyanin content of blackberries stored at 2, 5, or 10°C increased during storage (Perkins-Veazie et al. 1999a). Although anthocyanin content of blackberries stored at 2°C remained stable throughout 12 days of storage (Barth et al. 1995), after 7 days at 10°C it increased by 48 or 86%, depending on the cultivar (Perkins-Veazie et al. 1999a). Anthocyanin increased by approximately 33% in 'Navaho' blackberries when held for 21 days at 2°C, and by 60 and 85% when fruit was held for 14 and 7 days at 5 or 10°C, respectively (Perkins-Veazie et al. 1999a). Storage temperature has a major effect on anthocyanin accumulation, as higher temperatures seem to stimulate the synthesis of the pigment. Although anthocyanin content of blackberries tends to increase during storage, when blackberries were stored for 3 weeks at 3 ± 2°C total anthocyanin content decreased, most likely owing to aging of the fruit (Basiouny 1995) and to changes in pH of the juice and color of the fruit.

Total phenolic content of 'Arapaho' and 'Shawnee' blackberries stored for 7 days at 2°C significantly increased, but anthocyanin content and antioxidant activity decreased compared to initial values in fresh fruit. Following 2 additional days at 20°C the antioxidant activity of blackberries increased, most likely because of anthocyanin synthesis or increased availability of free anthocyanins in fruit stored at warmer temperatures, but was still lower compared to initial values in fresh fruit. Antioxidant activity, measured as oxygen radical absorbance capacity (ORAC), did not increase after storage of blackberries at 2°C (Perkins-Veazie et al. 1999b; Perkins-Veazie and Kalt 2002).

Time and Temperature Effects on the Visual Quality of 'Chester Thornless' Blackberries

The 'Chester Thornless' blackberries shown in Figures 3.1–3.5 were harvested at the shiny-black stage, but not overripe, from a commercial operation in Saint-Augustine-de-Desmaurs, Quebec, Canada, during the summer season (i.e., September). Promptly after harvest, fresh blackberries were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Visual quality of 'Chester Thornless' blackberries deteriorates during storage. In addition, the rate and type of deterioration is greatly affected by storage temperature. Although no visual changes in the black coloration of the fruit are noticeable during storage, berries show a significant reduction in their glossy appearance as storage progress, with the rate of loss increased with temperature (Figures 3.1–3.5).

Blackberries stored at 0°C maintain an acceptable appearance during 4 days. After 4 days, the fruit shows increased loss of glossiness, and the drupelets appear shriveled and dry. After 18 days at 0°C the fruit appears dry, shriveled, and dull in color (Figure 3.1).

When blackberries are stored at 5°C, loss of gloss and dull color develop much faster than at 0°C. After only 2 days the fruit appears dry and dull, and some of the fruit drupelets are dry and brown. Dryness and drupelet-browning increase as the storage time increases, and after 10–11 days decay is also evident at the stem-end of the fruit (Figure 3.2).

At 10°C, visual changes are faster than at 0 or 5°C, and after only 1 day 'Chester Thornless' blackberries appear dull in color, although not yet shriveled. After 8 days some drupelet discoloration develops at the stem-end. The drupelets appear reddish and leaky, and after 9–10 days mold growth is evident at the stem-end of the fruit (Figure 3.3).

The major changes in blackberries stored at 15°C are loss of glossiness and development of a dry appearance of the drupelets after 1 day (Figure 3.4). Although in this particular case no other visual changes are observed during storage, decay may eventually develop in blackberries stored at this temperature.

Blackberries stored at 20°C have a very dry appearance and dull color after only 1 day, and some of the drupelets at the equatorial part of the fruit show mold growth after 3–4 days of storage (Figure 3.5). Overall, changes in glossiness, shriveling, discoloration, dry appearance, and decay are the major visual quality changes that limit the postharvest life of blackberry fruit. During storage, blackberries lose their glossy dark color and become dull. In addition, the higher the storage temperature the faster these changes occur. 'Chester Thornless' blackberries stored at 0°C maintain a better visual quality for longer periods (4 days), when compared to fruit stored at higher temperatures. Blackberries stored at 5, 10, 15, and 20°C maintain an acceptable appearance during approximately 1 or 2 days, but afterward quality of the fruit deteriorates rapidly.

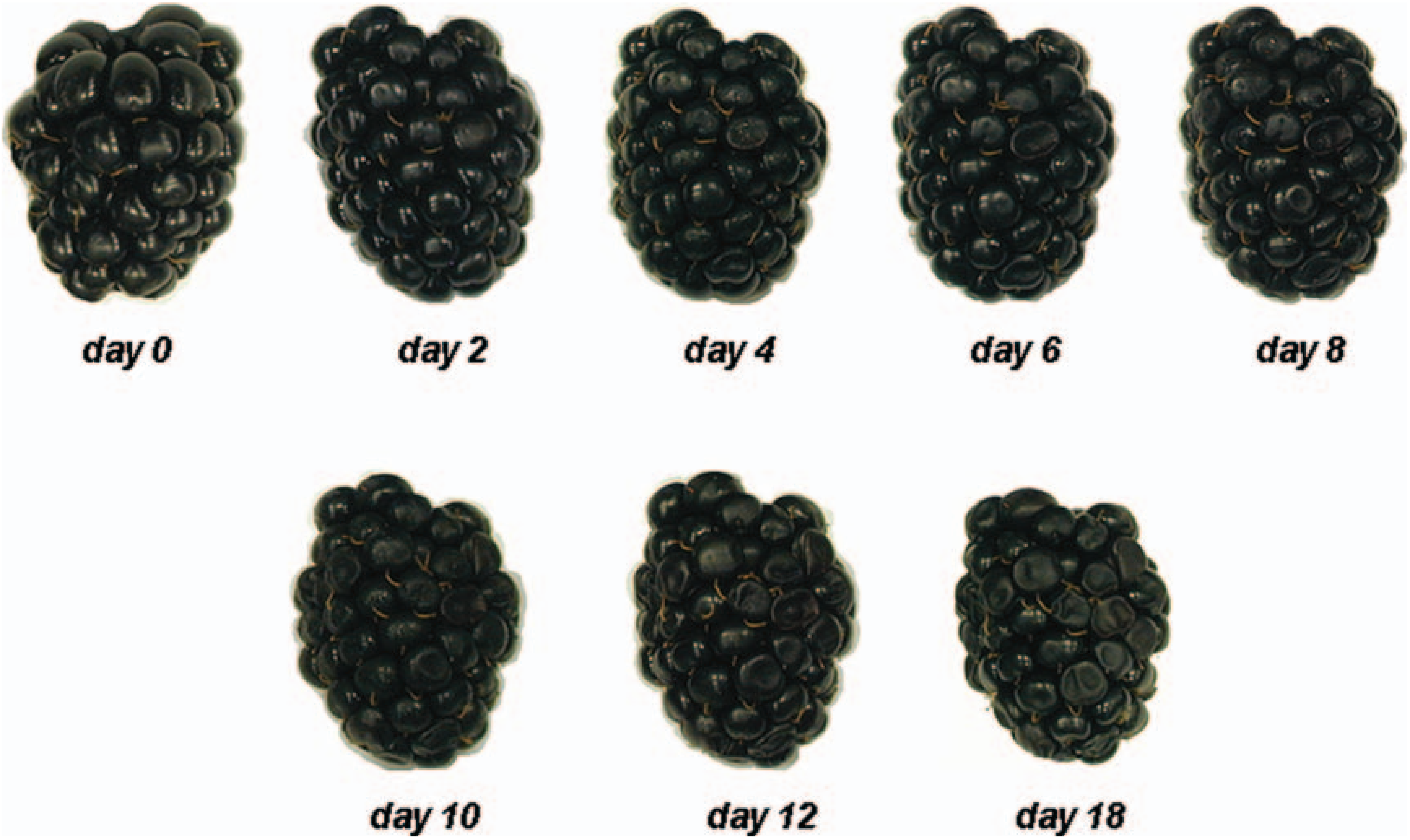
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Figure 3.1. Appearance of 'Chester' blackberry stored for 18 days at 0°C. The fruit maintains an acceptable appearance during 4 days, but after that time the fruit drupelets start to show signs of shriveling and loss of glossiness. After 18 days the blackberry appears dull, dry, and shriveled.

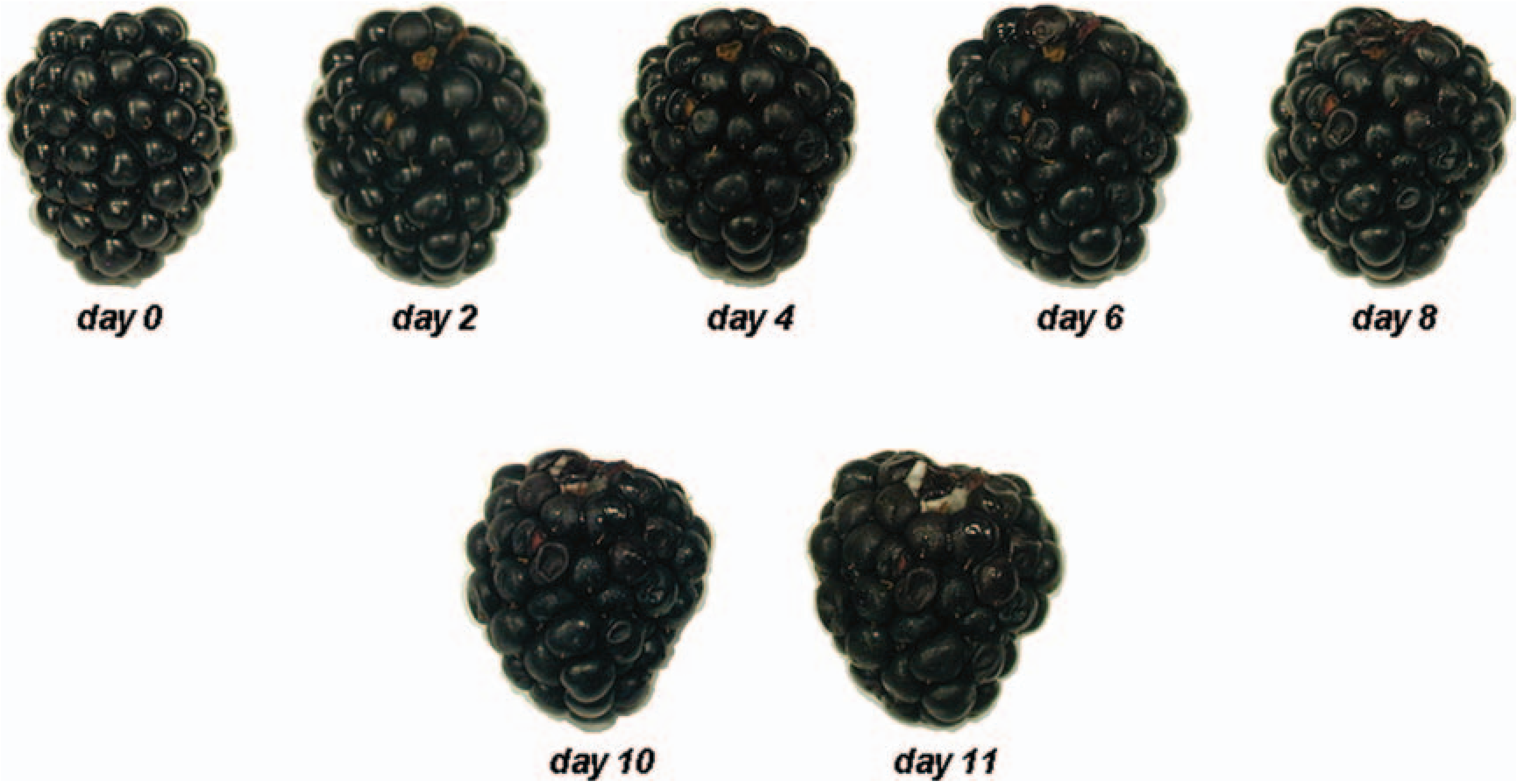

Figure 3.2. Appearance of 'Chester' blackberry stored for 11 days at 5°C. The fruit maintains an acceptable appearance during 2 days, but at that time the blackberry drupelets start to show minor signs of browning, shriveling, and loss of glossiness. After 10 days decay develops, and after 11 days the blackberry is decayed and leaky.

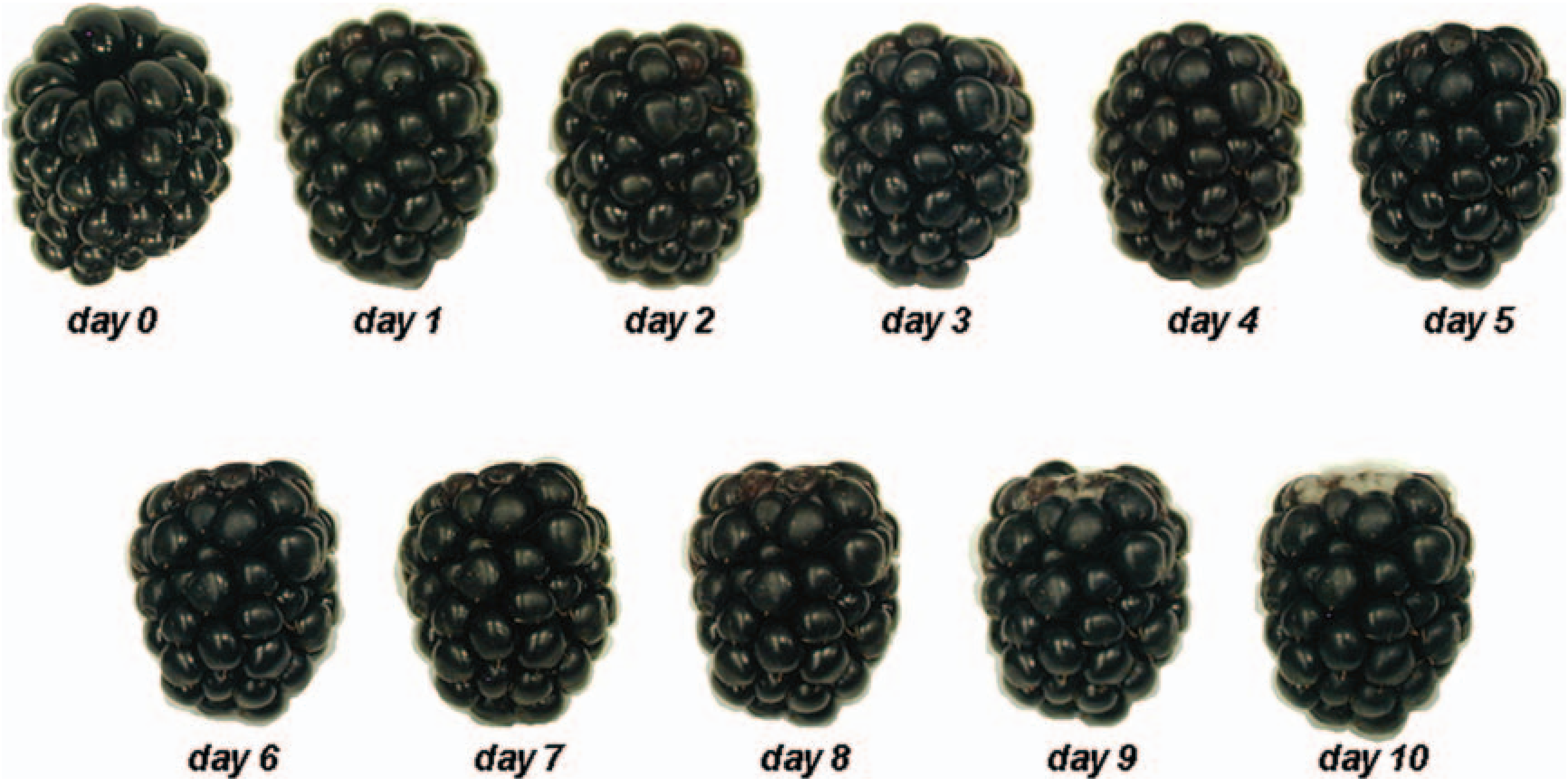
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Figure 3.3. Appearance of ‘Chester’ blackberry stored for 10 days at 10°C. The fruit maintains an acceptable appearance during 2 days, but at that time the fruit drupelets start to show minor signs of shriveling and loss of glossiness. After 8 days decay develops, and after 10 days mycelium is fully developed.

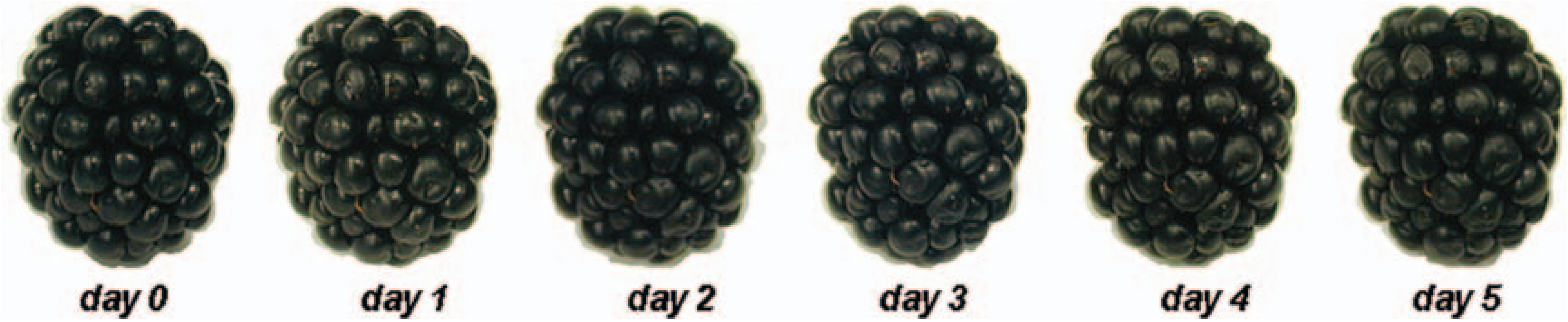

Figure 3.4. Appearance of ‘Chester’ blackberry stored for 5 days at 15°C. The fruit maintains an acceptable appearance during 2 days, but after that time drupelets are shriveled, and the blackberry appears dull and leaky.

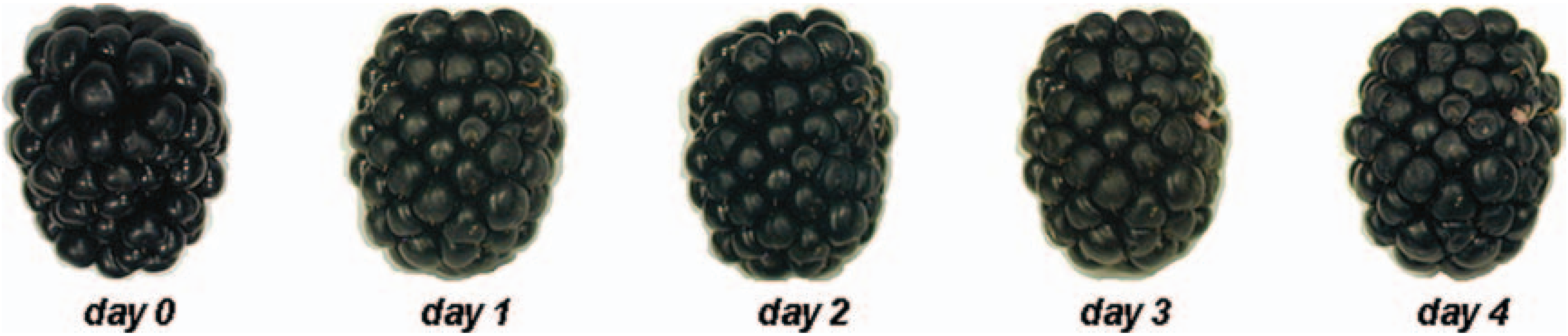

Figure 3.5. Appearance of ‘Chester’ blackberry stored for 4 days at 20°C. The fruit maintains an acceptable appearance during 1 day, but at that time the fruit drupelets start to show signs of shriveling and loss of glossiness. After 3 days, decay develops on blackberry surface.

BLUEBERRY

Scientific Name: *Vaccinium corymbosum*
Family: Ericaceae

Quality Characteristics

There are three main species of commercial blueberry plants: lowbush, highbush, and rabbiteye. Fruits of lowbush plants are much smaller than fruits of highbush or rabbiteye and are usually used only for processing. Rabbiteye plants are native to the southern regions of America, as they prefer warmer temperatures than northern highbush plants. Southern highbush is a mixture of species and was specifically developed for early fruiting crops in southern latitudes. Fruit from rabbiteye plants is usually slightly smaller and firmer, has a tougher skin, and is sweeter than the fruit from highbush plants. Northern highbush cultivars grow better in northern regions where excessively high temperatures do not occur (Kalt and McDonald 1996; Makus and Morris 1993; Moore 1993; Perkins-Veazie et al. 1995; Silva et al. 2005).

Blueberries usually have a grayish waxy deposit on the skin, which is called the waxy bloom. The amount of waxy bloom depends on the type of cultivar and may prevent moisture from being lost during storage (Magee 1999). The blue surface color can increase or decrease, from increased anthocyanin or from juice leakage. Changes in color, loss of firmness, and decay are the major factors that determine the quality of fresh blueberries (Cappellini et al. 1982; Sanford et al. 1991; Sapers et al. 1984). Blueberries harvested 60% blue are firmer than fruit harvested 100% blue and may develop a full blue color after 15 days of storage at 2°C, plus 3 days at 20°C. However, fruit that is picked at 60% rather than full blue often has a lower soluble solids content and higher acidity and is, therefore, less sweet (Beaudry et al. 1998).

Blueberry quality and maturity may also be evaluated according to the sugar, soluble solids content, and acidity of the fruit (Ballinger et al. 1978; Kalt et al. 1995). As the fruit matures, the content in soluble solids and sugars increases, whereas acidity decreases (Kalt and McDonald 1996). Blueberries designated for distant market shipment should have a soluble solids content-to-acidity ratio of no more than 20, whereas fruit for intermediate markets should have a soluble solids content-to-acidity ratio of no more than 27. Fruit with a ratio of about 30 should be marketed locally, and fruit with a ratio of 40 was considered overripe (Ballinger et al. 1978). Acidity and soluble solids content-to-acid ratio were inversely related to keeping-quality of blueberry fruit (Galletta et al. 1971).

Blueberry fruit contains on average 85% water, 14% carbohydrates, 0.7% proteins, and 3% fiber, 13 mg of vitamin C, and minor amounts of other vitamins per 100 g of fresh fruit (USDA 2006). Blueberries have also been considered among other fruits to be one of the richest sources of antioxidants such as total phenolics and anthocyanins (Kalt et al. 1999, 2000, 2001). However, maturity of the berries at harvest, genetic differences among cultivars, and preharvest environmental conditions may have a great effect on the antioxidant capacity of the fruit. For example, in blueberries harvested with 50–75% blue coloration, the antioxidant activity (determined as ferric-reducing antioxidant power), as well as total phenolic and anthocyanin content, was higher when compared to less mature fruit (Connor et al. 2002).

Optimum Postharvest Handling Conditions

Pre-cooling of blueberries right after harvest from ambient field temperatures to 5°C before packing is an efficient method of slowing microbial growth and extending the postharvest life of the fruit (Hudson and Tietjen 1981). Reducing delayed cooling from 16 to 2 hours at 30°C significantly reduced loss of water and softening of ‘Tifblue’ blueberries after storage (Tetteh et al. 2004). Compared to non-pre-cooled fruit, blueberries rapidly pre-cooled to 2°C had 60–80% less decay and were still marketable following a 3-day simulated transit period at 10°C and subsequent storage for 21 hours at 21°C (Hudson and Tietjen 1981). In addition, compared to delay-cooled fruit, fast pre-cooling of blueberries resulted in approximately 35% fewer decayed berries after storage at 0°C (Jackson et al. 1999). Blueberries for the fresh market should not be exposed to temperatures higher than 10°C and preferably should be held at or near –0.5–1°C, with a relative humidity higher than 90% (Ballinger et al. 1978; Perkins-Veazie 2004b; Sanford et al. 1991).

Temperature Effects on Quality

Blueberries have been exported to Western Europe from North America and Chile via airfreight, arriving at the market within approximately 48 hours after harvest (Beaudry et al. 1998; Miller and Smittle 1987; Miller et al. 1984). However, the optimum temperature is seldom maintained during air transportation or truck shipment, resulting in a rapid quality deterioration of the fruit compared with fruit maintained at an optimum temperature of about 0–1°C (Ballinger et al. 1978; Cappellini et al. 1983; Miller and Smittle 1987; Perkins-Veazie 2004b). Occasionally, blueberries are shipped to local markets with little or no refrigeration, whereas for distant markets they are usually shipped by truck at 5–7°C (Hudson and Tietjen 1981). For example, during simulated airfreight, weight loss of blueberries was similar to that during a 7-day exposure at 3°C (Miller and Smittle 1997). Furthermore, at the retail level, blueberries are often displayed with little or no refrigeration. Consequently, decay of blueberries greatly increased when fruit was stored at temperatures above 1.1°C, and when held at 22.2°C, the fruit deteriorated very rapidly, reaching the minimum acceptable level of 15–20% decay within 1–5 days (Ballinger et al. 1978; Cappellini et al. 1982). Southern highbush blueberries stored at 2°C for up to 7 days maintained an acceptable quality with insignificant changes in weight, percentage of decay, or changes in soluble solids, acidity, or pH. However, when transferred to 21°C for 2 days, weight loss and decay increased significantly. Therefore, quality of blueberries stored continuously at 2°C was acceptable up to 11 days, whereas retail quality was reduced to 3 days after holding the berry 4 days at 21°C (Lang and Tao 1992). Rabbiteye blueberries covered with a thin polyethylene plastic film and stored for 15 days at 5°C had an attractive appearance with no signs of shriveling (Basiouny and Chen 1988). Blueberries packed in plastic films and stored at 4°C scored higher for blue color, sweet and acidic taste, blueberry flavor, crispness, firmness, and juiciness, whereas fruit stored at 12°C scored higher for storage odor, intensity of taste, bitter taste, and storage flavor (Rosenfeld et al. 1999). Increasing the storage temperature also results in increased incidence of shriveled and decayed blueberries, as well as increased fruit breakdown (Sanford et al. 1991). Ballinger et al. (1978) determined 20% loss to be a moderated level of quality deterioration above which blueberries should not be sold in the fresh market, whereas Cappellini et al. (1982) found an average of 15% defective fruit in consumer samples. Sanford et al. (1991) reported very little decay on wild lowbush blueberry stored at temperatures from 0 to 20°C. Generally, decay contributed to an average loss of only 1–2% in fruit stored at 15 or 20°C, respectively, and 0.1–0.4% in fruit stored at 0 or 5°C, respectively. However, decay was much higher in northern highbush 'Bluechip' blueberries stored at 21°C for 7 days. It ranged from 3.6% for dry-handled berries to 63.5% when berries were handled wet (Cline 1997). Increasing the storage temperature from 0 to 20°C resulted in higher levels of berry flesh disintegration and collapse, shriveling, and decay (Sanford et al. 1991). 'Patriot' blueberries stored at 0 or 5°C for 14 days developed the smallest amount of decay compared with fruit stored at higher temperatures; 5–7.5% decay in fruit stored at 0°C, and 7.5–10% decay in fruit stored at 5°C (Nunes et al. 2004). Likewise, decay in 'Climax' rabbiteye blueberries grown in Florida reached approximately 7% after 3 weeks of storage at 1°C (Miller et al. 1993). Low incidence of decay (1%) and leakage after storage of 'Climax' and 'Jubilee' for 28 days at temperatures between 1 and 3°C was attributed to small, dry steam scars, low storage temperature, early morning hand picking, and prompt storage (Magee 1995). As storage temperature increased, decay increased from 10 to 15% in 'Patriot' blueberries stored at 10°C for 12–14 days, respectively, whereas after 12 days at 15–20°C, the percentage of decayed fruit reached approximately 13 and 18%, respectively (Nunes et al. 2004).

The color of blueberries changes during storage, and L* value (lightness) of 'Patriot' berries decreased slightly, from approximately 31.0 at harvest to 28.0 after 14 days, regardless of the storage temperature. These differences indicate that the fruit lost its waxy bloom or bright color during storage and became darker. Hue of blueberries stored at 10, 15, or 20°C slightly decreased from 299.9 at the time of harvest to approximately 295.7 after 2 days, and increased thereafter to reach levels comparable to initial values. Blueberry hue increased slightly to approximately 302.8 after 14 days when stored at 0 or 5°C. After 14 days, the berries were more purplish–dark blue than blue (higher hue), compared with freshly harvested fruit. Blueberry chroma decreased from 7.5 at the time of harvest to approximately 5.9 after 12 or 14 days, irrespective of the storage temperature. Therefore, blueberries became less vivid (lower chroma values) during storage than at harvest. Color changes visually observed during storage of 'Patriot' blueberries at different temperatures were more evident than changes in the instrumental color measurements such as hue or chroma (Nunes et al. 2003). However, L* value was a good indicator of loss of brightness, which was in fact a more important criterion for evaluating the changes in color than the blue color of the fruit. Color measurements made on blueberries showed a close relationship between the L* value (higher L* values indicating lighter-colored fruit) and visual assessment of waxy bloom (Sapers et al. 1984). Loss of the waxy bloom may be attributed not only to the changes in the color of the fruit during storage but also to overmanipulation of the fruit (Nunes et al. 2003).

In general, storage temperature has a significant effect on blueberry firmness; that is, as storage temperature increases the firmness of blueberries decreases (Jackson et al. 1999; NeSmith et al. 2005; Sanford et al. 1991). Although softening of 'Patriot' blueberries increased as temperature increased, it never reached unacceptable levels, even after 14 days at 20°C. Blueberries of the cultivar 'Patriot' are bigger and firmer than many other highbush blueberry cultivars (Hepler and Draper 1976; Øydvin and Øydvin 1999), and that might explain the minimal softening of the fruits even when stored at temperatures higher than 0°C (Nunes et al. 2004).

Hand-harvested blueberries are generally firmer compared to machine-harvested fruits. After storage for 8–10 days at 1°C the decrease in firmness of hand-harvested blueberries was only 1.5 and 4.7% compared to machine-harvested fruits, which were 36.2% less firm than hand-harvested fruit (Nunez-Barrios et al. 2005). Likewise, Magee (1999) found that hand-harvested southern highbush cultivars showed a decrease in firmness between approximately 1.4–2.7% after storage for 28 days at temperatures between 1 and 3°C. Shriveling paralleled fruit softening in southern highbush blueberries, increasing during storage by about 1.7–3.3% (Magee 1995).

Storage temperature also influences the rate of moisture loss, particularly when the fruit is handled under very low humidity levels. When handled under the optimum temperature and humidity conditions (0–1°C and with a relative humidity of 90% or above), blueberries stored for 14 days may lose less than 5% of their initial weight (Jackson et al. 1999; Miller et al. 1993; Nunes et al. 2004), whereas, according to the literature, the maximum weight loss before blueberries become nonsaleable is approximately 5–8% (Sanford et al. 1991). Decreasing the field temperature of lowbush blueberry fruit from 26 to 5°C after 4–5 hours postharvest resulted in a weight loss of only 0.21% after 21 days at 0°C (Jackson et al. 1999). Depending on the cultivar and species, weight loss of highbush blueberries stored at 1°C for 2 weeks may vary from 2.5 to 17.5% (Bounous et al. 1997). Weight loss of southern highbush blueberries from two harvests stored at 2°C increased from 0.8 to 1.3%, or from 1.3 to 4.1% after 3 and 5 days of storage, respectively (Lang and Tao 1992), but remained within the limits of acceptability according to Sanford et al. (1991). Conversely, southern highbush blueberry cultivars stored for 28 days at temperatures between 1 and 3°C and 88–90% relative humidity had 5.7–8.5% weight loss, depending on the cultivar, stem scar, and berry size (Magee 1995). During simulated marketing condition (21 days at 5°C), weight loss of machine-harvested blueberry cultivars varied between 4.5 and 6.7%, depending on the cultivar (Smittle and Miller 1988).

Chemical composition of the blueberry, as well as color change and texture, is affected by storage time and temperature and species. Soluble solids content and pH increased during storage, whereas acidity decreased in blueberries stored at temperatures higher than 0°C (Basiouny and Chen 1988; Beaudry et al. 1998; Kalt and McDonald 1996; Perkins-Veazie et al. 1995; Sanford et al. 1991). However, changes were slowed to a nonsignificant level in lowbush and rabbiteye blueberries stored at temperatures of around 1°C (Jackson et al. 1999; Miller et al. 1993). Southern highbush blueberries stored at 2°C showed an increase in soluble solids content and acidity accompanied by a decrease in pH after 7 days of storage (Lang and Tao 1992). Conversely, blueberries stored at 4°C had a higher pH and soluble solids content and lower acidity compared to fruit stored at 12°C (Rosenfeld et al. 1999). In rabbiteye blueberries, pH decreased significantly after 14 days of storage at 5°C (Smittle and Miller 1988).

When blueberries were harvested before attaining the fully blue color stage, a considerable increase in antioxidant capacity, total phenolic content, and anthocyanin content occurred during storage at 5°C (Connor et al. 2002). Increases in anthocyanin content between 22 and 55% were also reported for the southern highbush cultivars ‘Cape Fear’ and ‘Sierra,’ respectively, during storage for 21 days at 5°C (Perkins-Veazie et al. 1995), whereas in lowbush blueberries stored for 2 weeks at 1°C, anthocyanins increased by 18% (Kalt and McDonald 1996). Likewise, the development of anthocyanin pigments in rabbiteye blueberries continued to increase steadily during storage at 5°C, and after a 45-day storage period an increase of approximately 55 and 71% was observed in the anthocyanin content of ‘Tifblue’ and ‘Bluegem,’ respectively (Basiouny and Chen 1988).

Total sugars, glucose, fructose, acidity, and anthocyanin contents increased after storage of highbush blueberry cultivars for 28 days at temperatures between 1 and 3°C. However, when ‘Bluecrop’ blueberries were held at 20°C, vitamin C content significantly decreased after 8 days of storage (Kalt et al. 1999).

Time and Temperature Effects on the Visual Quality of ‘Patriot’ Blueberries

‘Patriot’ blueberries shown in Figures 3.6–3.10 were harvested at the fully ripe stage from a commercial operation in Saint Nicolas, Quebec, Canada, during the summer season (i.e., July). Promptly after harvest, fresh blueberries were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Postharvest visual quality of ‘Patriot’ blueberries is greatly affected by storage time and temperature. Changes in the color of the blueberry during storage are mainly due to loss of the waxy bloom accompanied by changes in the blue color of the fruit. Although not uniform, the waxy bloom of ‘Patriot’ blueberries disappears after approximately 8 days, regardless of the storage temperature (Figures 3.6–3.10). Parallel to changes in waxy bloom of the berries, the color changes from a bright purplish-blue to a darker blue, particularly in blueberries stored at 15 and 20°C (Figures 3.9 and 3.10).

Blueberries stored at 0°C maintain an acceptable visual quality during 12–14 days. However, after 12 days the berries appear less glossy and slightly shriveled. After 14 days shriveling is evident, and the color of the fruit is a dull dark blue (Figure 3.6). When blueberries are held at 5°C, the first signs of shriveling appear after 6 days and increase to objectionable levels after 14 days. Appearance of the fruit is acceptable for 10–12 days, then starts to deteriorate. After approximately 10 days the color of the blueberries darkens, and after 14 days the berries appear shriveled and dull in color (Figure 3.7).

After 6–8 days at 10°C, the appearance of blueberries starts to deteriorate, the fruit develops a very dark blue dull color, and shriveling becomes unacceptable after 12 days of storage. After 14 days of storage, the berries appear very dark, shriveled, soft, and overripe (Figure 3.8).

The first signs of shriveling appear after 4 days in blueberries stored at 15°C, with obvious shriveling after 10 days. After 4–6 days, the general appearance of 'Patriot' blueberries starts to deteriorate, and after 14 days the fruit develops a very dark color and appears extremely shriveled, soft, and overripe (Figure 3.9).

Blueberries maintained an acceptable appearance during 4 days of storage at 20°C. After 6 days, the fruit starts to show slight signs of shriveling, and shriveling becomes severe as the storage progresses. After 8 days, shriveling becomes objectionable, and the berries appear extremely shriveled, dry, and overripe after 14 days (Figure 3.10).

In summary, deterioration of visual quality of blueberries during storage is mainly the result of changes in the natural waxy bloom of the fruits and darkening of the color from a purplish-blue at the time of harvest to a dark blue during storage. Shriveling of the fruit skin, to a wrinkled and dry appearance, with storage time is also an important limiting visual quality factor. Visual quality changes occur faster at higher temperatures and with extended storage periods and reduce the marketability of the fruit. 'Patriot' blueberries stored at 0°C maintain a better visual quality for longer periods (14 days), when compared to fruit stored at higher temperatures. Blueberries stored at 5, 10, 15, and 20°C maintain an acceptable appearance during 12, 8, 6, and 4 days, respectively, but after that quality of the fruit deteriorates rapidly.

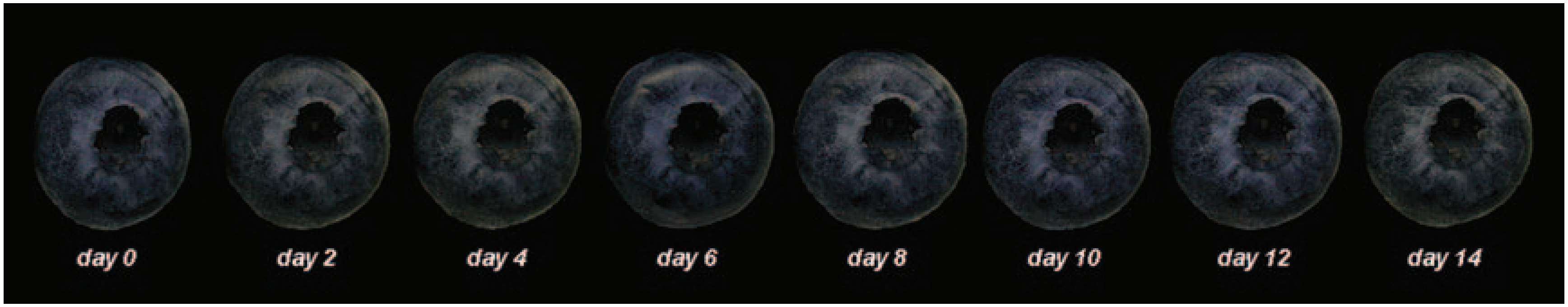
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Figure 3.6. Appearance of 'Patriot' blueberry stored for 14 days at 0°C. The berry maintains an acceptable appearance during 14 days. However, after 12 days shriveling becomes objectionable.

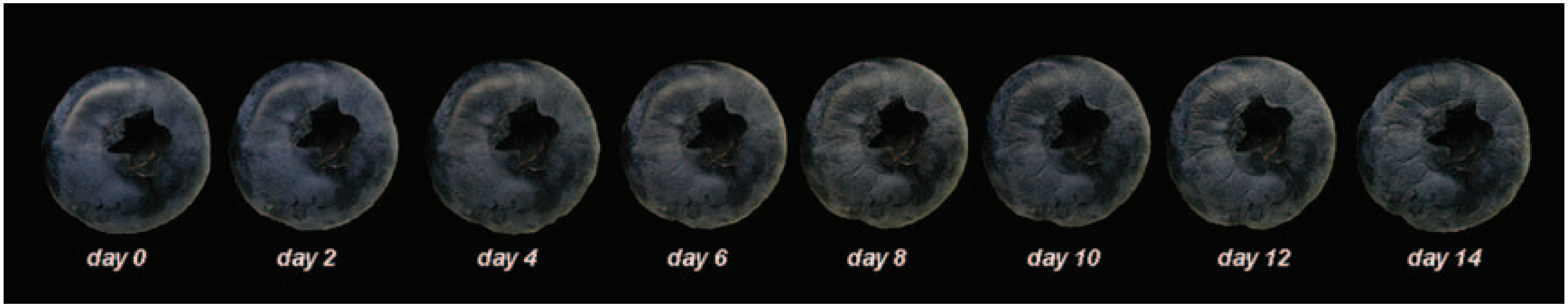
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Figure 3.7. Appearance of 'Patriot' blueberry stored for 14 days at 5°C. The berry maintains an acceptable quality during 8 days. After 8 days shriveling becomes apparent, and after 10 days the berry loses its natural waxy bloom and appears dull and darker.

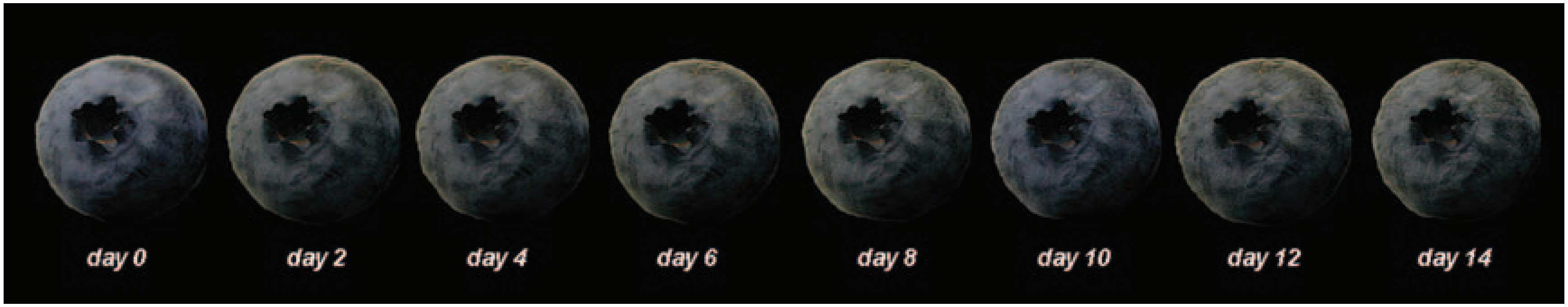
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Figure 3.8. Appearance of 'Patriot' blueberry stored for 14 days at 10°C. Fruit maintains an acceptable quality during 6 days. After 6 days the berry loses its natural waxy bloom and develops a dark and dull color. Shriveling attains a maximum acceptable after 12 days, and after 14 days the berry appears overripe.

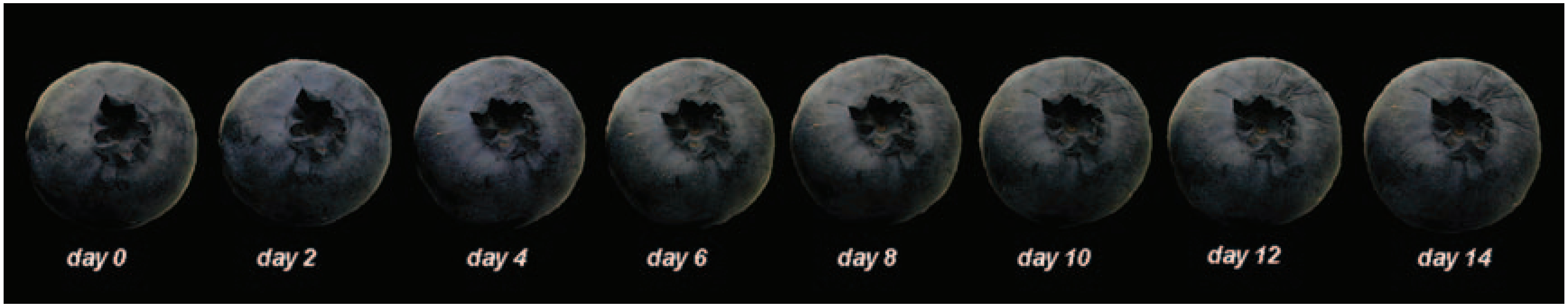
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Figure 3.9. Appearance of ‘Patriot’ blueberry stored for 14 days at 15°C. The berry maintains an acceptable quality during 4 days. After 4 days the berry loses its natural waxy bloom and develops a dark and dull color. Shriveling attains a maximum acceptable after 8 days, and after 14 days the berry appears overripe.

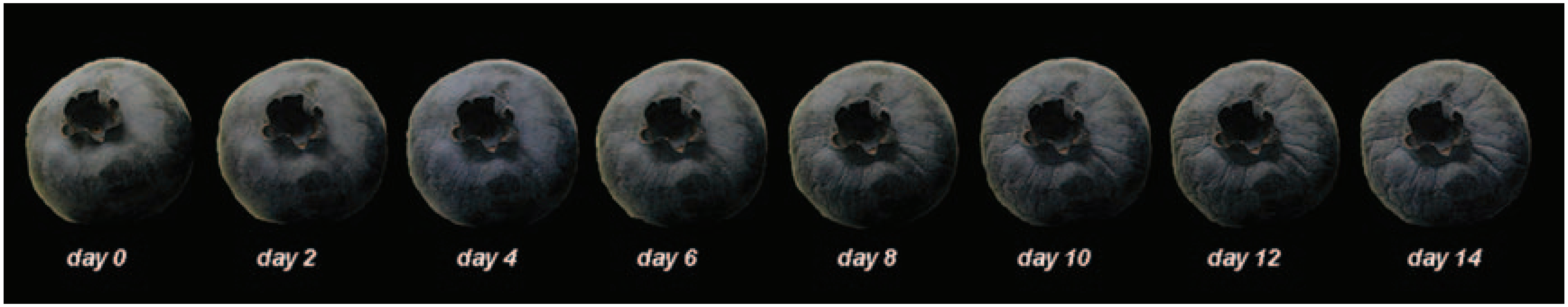
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Figure 3.10. Appearance of ‘Patriot’ blueberry stored for 14 days at 20°C. The berry maintains an acceptable quality during 2–4 days. After 4 days the berry loses its natural waxy bloom and develops a dark and dull color. Shriveling attains a maximum acceptable after 8 days, and after 14 days the berry appears extremely shriveled and overripe.

CURRANT

Scientific Name: *Ribes nigrum* L. (black currant) and *Ribes rubrum* L. (red currant)
Family: Grossulariaceae

Quality Characteristics

Currants are grown mainly in the northern temperate regions of Europe and North America, but some species are also found in Asia, the Andes, and northwest Africa. However, most of the worldwide production of currants is in northern Europe and New Zealand. The main producers are Poland, Russia, Germany, the Scandinavian countries, and Great Britain. Black currants (*Ribes nigrum* L.) are the major cultivated crop, but other species such as red currants (*Ribes rubrum* L.), pink currants (*Ribes petraeum* L.), and white currants (*Ribes sativum* L.) are also commercially grown (Barney and Hummer 2004; Brennan 1996; Hummer and Barney 2002; Toldam-Andersen and Jensen 2004). Although not frequently seen in the North American fresh market, currants have been used for centuries as food, medicine, or ornamental shrubs, particularly in Europe. In North America relatively few people know what currants are or have ever tasted them fresh. When available on the fresh market, currants are often very tart and do not have a pleasant taste, mostly because they are picked before attaining the full ripe stage (Barney and Hummer 2004). Because of lack of knowledge about the fruit, low acceptability by the consumer, and thus reduced market demand, most of the black currants grown worldwide are intended for juice, jam, or jelly (Hukkanen et al. 2002; Lister et al. 2002; Nes 1993).

Red and white currants are usually harvested when all the fruit in the cluster is ripe. Because the fruit has a very delicate skin, tearing easily when berries are pulled from the clusters, red and white currants are usually hand-harvested as a cluster. Black currants are firmer and can be pulled individually from the clusters, or the entire cluster may be hand-harvested. Unlike other soft fruits such as strawberries and raspberries, which change quickly from ripe to overripe if left on the plant, currants can stay on the shrub for 1–4 weeks or more without becoming overripe (Barney and Hummer 2004). For local fresh market and home consumption, currants should be harvested fully ripe, corresponding to about 3 weeks after development of full color. For shipping, fruits should be harvested at the mature stage but before ripening. Fully ripe currants are sweeter and taste better than unripe fruit, and when completely ripe, the berries are soft, tasty, and fully colored with no trace of green on the stem ends. When harvested overripe, fruit shrivels and becomes very soft (Barney 1996; Barney and Hummer 2004).

Red currants are usually harvested before the skin changes from bright to dull red, when the soluble solids content attains 9.5–14% and acidity is around 2%. However, depending on the cultivar, the soluble solids content of red currants may vary at the time of harvest from 7.4 to 11.5% (Pantelidis et al. 2006). The composition of white to very dark red currants is variable, depending on the cultivar and currant color. For example, white currants contain on average 7.2–10.3% sugar and 2.1 and 3.0% acid, pink currants contain 8.6% sugar and 2.4% acid, bi-colored currants contain 12.8% sugars and 3.1% acids, red cultivars contain 7–12.2% sugars and 1.9–3.3% acid, dark red currants contain 8.8–12.8% sugar and 2.8–3% acid, and very dark currants contain 9.2% sugar and 3.4% acid (Toldam-Andersen and Jensen 2004).

Black currants should be harvested uniformly black or very dark blue with no trace of green on the skin, when the soluble solids content attains 13.5–26%, total sugars range from 6 to 9%, and acidity is approximately 3–4.8% (Libek and Kikas 2002; Nes 1993; Pluta and Zurawicz 2002; Prange 2004; Sasnauskas et al. 2004; Stanisavljevié et al. 1999). Black currants are highly acidic, with pH at harvest ranging from 2.8 to 3.5 among cultivars (Stanisavljevié et al. 1999).

Currants in general and black currants in particular are considered an excellent source of vitamin C. Black currants contain on average 79–81% water, 1.4% protein, 15.4% carbohydrate, 322 mg of potassium, 86–250 mg of vitamin C, and 230 IU of vitamin A per 100 g fresh fruit, as well as other vitamins and minerals in minor concentrations (Benvenutti et al. 2004; Libek and Kikas 2002; Lister et al. 2002; Nes 1993; Pluta and Zurawicz 2002; Sasnauskas et al. 2004; Stanisavljevié et al. 1999; USDA 2006; Zadernowski et al. 2005). Black currants are excellent sources of antioxidants such as anthocyanins, tannins, and other phenolic compounds (Lister et al. 2002). Depending on the cultivar, black currants may contain from 520 to 1,150 mg of total polyphenols and 152–400 mg of anthocyanins per 100 g fruit fresh weight, and a very high antioxidant capacity, owing to the generous amounts of total phenolic compounds, anthocyanins, and vitamin C (Benvenutti et al. 2004; Lister et al. 2002; Pluta and Zurawicz 2002; Zadernowski et al. 2005).

Red and white currants contain on average 84% water, 1.4% protein, 14% carbohydrate, 4% fiber, 275 mg of potassium, and 22–53 mg of vitamin C per 100 g fruit fresh weight, and other vitamins and minerals in minor concentrations (Benvenutti et al. 2004; Pantelidis et al. 2006; USDA 2006). Depending on the cultivar, red currants may contain from 1.1 to 136 mg of anthocyanins and 370–506 mg of total phenolics per 100 g fruit fresh weight, whereas the antioxidant capacity of the fruit may vary from 40 to 63 μmole/g fruit dry weight (Benvenutti et al. 2004; Pantelidis et al. 2006). White currants do not contain anthocyanins but are better sources of vitamin C (60–65 mg of vitamin C per 100 g fruit fresh weight) than red currants are (Kampuse et al. 2005).

Optimum Postharvest Handling Conditions

Currants should be pre-cooled immediately after harvest, especially when intended for the fresh market. Because currants are not chilling sensitive, they can be pre-cooled to −0.5–0°C. Therefore, to extend postharvest life and maintain a good fruit quality during storage, currants should be pre-cooled to 1°C within 2–4 hours after harvest and kept under refrigerated conditions at −0.5–0°C and 95% relative humidity. Under such conditions the expected postharvest life can be 1.5 and 2.5 weeks to a maximum of 4 weeks for black and red currant, respectively (Barney and Hummer 2004; Hardenburg et al. 1986; Hummer and Barney 2002; Kader 2002; Prange 2004).

Temperature Effects on Quality

Possibly owing to the relatively low commercial value of currant grown for the fresh market, very little information was found in the existing literature regarding the effects of temperature and humidity on the sensorial or compositional quality of currants. One study reported that when black and red currants were stored at 18°C, fruit shelf life was reduced to 2 days (Agar et al. 1997). Others reported that weight loss and decay increased when red currants were stored for 25 weeks at 1°C, and ascorbic acid content was significantly reduced when black currant was stored either at 1°C or under a fluctuating temperature regimen (Roelofs and Waart 1993).

When red currant cultivars were stored for 8–25 weeks at 1°C, drying through the fruit stalk and weight loss were higher during the first 8–11 weeks of storage. After 7–10 weeks of storage, weight loss of red currants was 4.75% and increased to 8.29% after 21–24 weeks of storage. Weight loss was mainly attributed to drying of the fruit stalks followed by fruit dryness (Agar et al. 1997; Roelofs and Waart 1993; Viola et al. 2000).

Decay increased during storage of red currant cultivars stored for 8–25 weeks at 1°C, with 90% of berries having decay after 14 weeks (Roelofs and Waart 1993). Initial symptoms of gray mold rot, caused by *Botritis cinerea*, appeared as small brown spots and enlarged quickly if the berries were held at temperatures of 10°C or higher. As storage progresses the entire berry may be affected with a soft rot (Ryall and Pentzer 1982; Salunkhe and Desai 2000).

Vitamin C content of currants decreases with increasing storage temperature. Black currants stored at 22°C had 10–20% lower levels of vitamin C compared to fruit stored at 5°C. After only 24 hours of storage, vitamin C content of black currants stored at 5°C was significantly higher (100 mg per 100 g fruit fresh weight) than that of currants stored at 22°C (76.7 mg per 100 g fruit fresh weight) (Häkkinen et al. 2000). When black currants were stored at 1°C, the initial ascorbic acid content of the fruit decreased from approximately 92 mg to 75 mg per 100 g fruit fresh weight after 21 days of storage. When currants were then transferred to 20°C for 2 additional days, ascorbic acid content further decreased to 60 mg per 100 g fruit fresh weight (Agar et al. 1997). Ascorbic acid content of black currants decreased sharply when the fruit was held for 10 days at temperatures fluctuating between 10 and 20°C. Under such conditions, the initial ascorbic acid of the fruit was reduced by 47–61%, depending on the cultivar and initial ascorbic acid content of the fruit (Viola et al. 2000).

Time and Temperature Effects on the Visual Quality of ‘Consort’ and ‘Red Lake’ Currants

‘Consort’ black currants and ‘Red Lake’ red currants shown in Figures 3.11–3.20 were harvested at the fully ripe stage from a commercial operation near Quebec City, Canada, during the summer season (i.e., August). Promptly after harvest, fresh currants were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Visual quality of ‘Consort’ black currants declines during storage, regardless of the storage temperature. Although no visual changes in the black coloration of the fruit are noticeable during storage, black currants show a slight reduction in glossy appearance during storage. Major changes in the visual quality of the fruit are most likely related to loss of moisture during storage. Berry stalk drying and browning and berry shriveling are the major visual quality changes in black currants during storage, particularly at temperatures higher than 0°C (Figures 3.11–3.15).

Black currants stored at 0°C maintain an acceptable visual quality for 20 days. After 16 days, the berry stalks appear slightly dryer compared to initial storage (day 0), and some berries show minor signs of shriveling, but the overall visual quality of the currants remains acceptable (Figure 3.11).

When black currants are stored at 5°C, berry shriveling develops much faster than at 0°C. After 16 days, some of the berries develop minor shriveling, increasing to significant shriveling after 20 days. After 20 days berry stalks appear less green and dryer than initially, yet there are no significant changes in the color of the berries (Figure 3.12).

At 10°C, visual changes in black currants occur more rapidly than at 0 or 5°C. After 12 days some berries of the 'Consort' black currant appear shriveled and with small brown spots. Shriveling continues to increase during storage, and after 16 days most of the berries are affected by shriveling and some by decay. At this time, some berries start to leak, and the berry stalks appear dry and brownish-green, particular at the lower part of the cluster (Figure 3.13).

The major changes in black currants stored at 15°C are loss of glossiness, development of decay, and dry brownish appearance of the berry stalks after 8–10 days. As storage progresses, shriveling and decay increases, and after 14 days most of the berries look dull in color, dry, and decayed. At this point, berry stalks are completely dry and brown (Figure 3.14).

Black currants stored at 20°C have a very dry appearance and dull color after 8 days. After 12 days, the currants appear dull in color, most of the berries are shriveled, and some have very small brownish spots. The berry stalk appears completely dry and brown after 8 days (Figure 3.15). Although no visual mycelium growth is observed in this particular case, decay may eventually develop in fruit stored at this temperature.

Overall, changes in berry glossiness, shriveling, dry appearance, and decay and discoloration of the berry stalk are the major visual quality factors that limit the postharvest life of 'Consort' black currants. During storage, black currants lose their glossy dark color and become dull, with changes occurring more rapidly as the storage temperature increases. 'Consort' black currants stored at 0°C maintain a better visual quality for longer periods (20 days), when compared to fruit stored at higher temperatures. Black currants stored at 5, 10, 15, and 20°C maintained an acceptable appearance for about 12, 10, 8, and 6 days, respectively; thereafter quality of the fruit deteriorated rapidly.

Changes in the visual quality of 'Red Lake' red currants after harvest are also greatly influenced by storage duration and temperature. Red currants stored at 0°C maintained an acceptable visual quality for 16 days and then started to show minor signs of shriveling and loss of glossiness. Shriveling and dryness of the berry stalk increased during storage, and after 24 days some berries showed severe signs of shriveling, and the berry stalk was dry and less green (Figure 3.16).

Red currants stored at 5°C maintain an acceptable appearance for 12 days, but then berries begin to show shriveling and loss of glossiness. Shriveling continues to increase during storage, and after 22 days the berries appear darker and less glossy. Some of the berries show severe signs of shriveling. Berry stalks lose green color during storage, and after 22 days appear less green and more dry than at harvest (Figure 3.17).

Accelerated decay causes the red currant berries to shatter, and after only 4 days at 10°C two of the berries in the cluster were completely decayed and leaky and had to be discarded. The remaining berries maintain an acceptable appearance for 8 days, after which signs of shriveling and loss of glossiness developed. After 22 days the berries were less glossy and more dry, whereas the berry stalk was completely dry and brown (Figure 3.18).

When stored at 15°C, 'Red Lake' red currants maintain acceptable appearance for only 2 or 4 days, then start to show minor signs of shriveling and loss of glossiness. Decay develops in some of the berries after 8 days, continues to develop, and spreads to other berries as storage progresses. After 14 days most of the berries have moderate to severe decay. The berry stalks dry and darken during storage and appear extremely brown and dry after 14 days (Figure 3.19).

Postharvest life of red currants stored at 20°C is extremely short, with loss of gloss, shrivel, and decay after only 2 days. After 16 days at 20°C, most of the berries in the cluster were decayed and appeared dull, with the berry stalk dry and less green (Figure 3.20).

In summary, loss of glossiness, shriveling, decay, and browning and dryness of the stalk are the most important visual factors that limit the visual quality of 'Red Lake' red currants during storage. Red currants maintain an acceptable visual quality for longer periods if stored at 0°C (16 days), and as temperature increases berry quality deteriorates faster. Red currants stored at 5, 10, 15, and 20°C maintain an acceptable visual quality for 12, 8, 2, and less than 2 days, respectively.

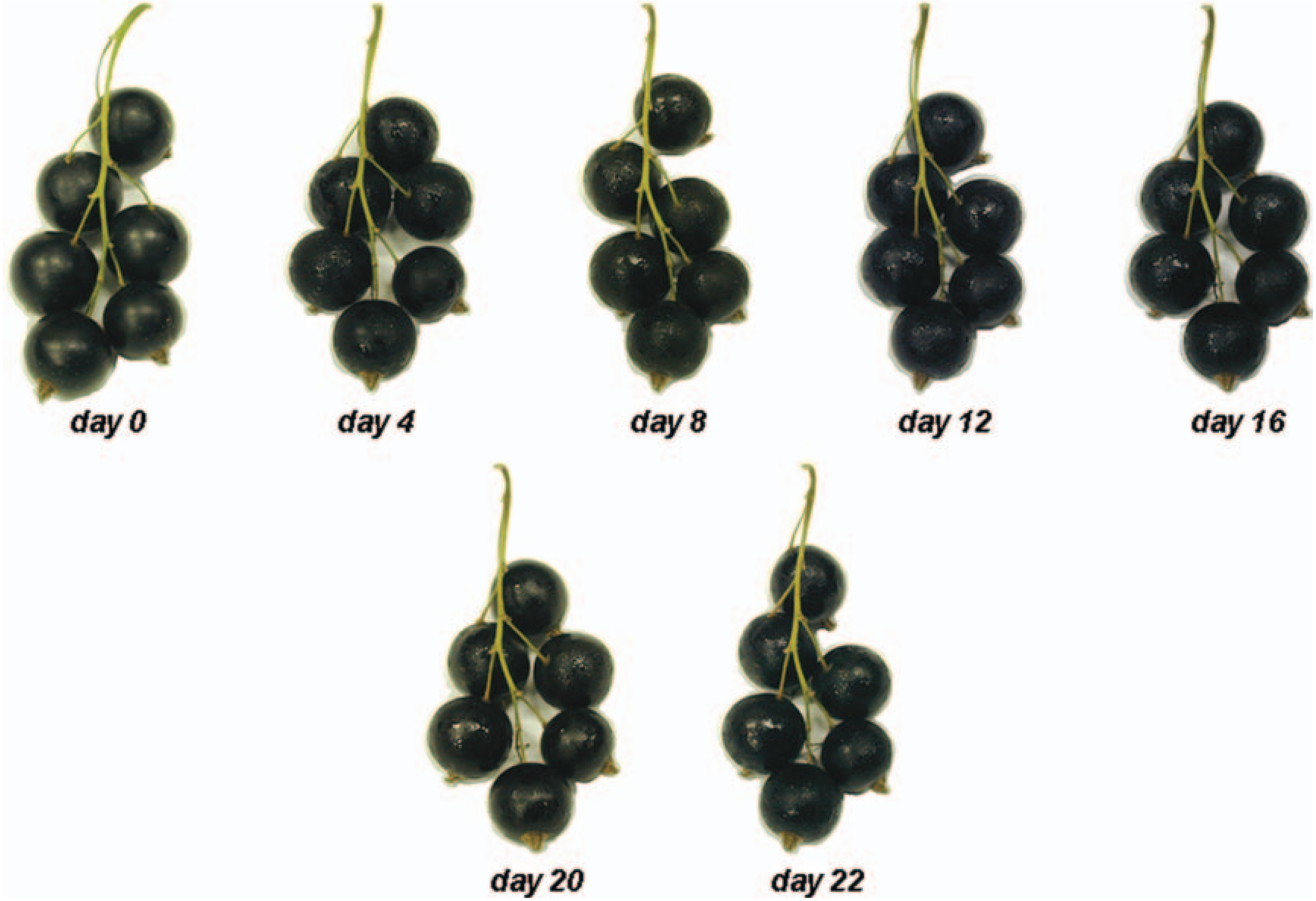
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Figure 3.11. Appearance of 'Consort' black currant stored for 22 days at 0°C. The berries maintain an acceptable appearance during 16 days, but at that time the berries start to show minor signs of shriveling and loss of glossiness.

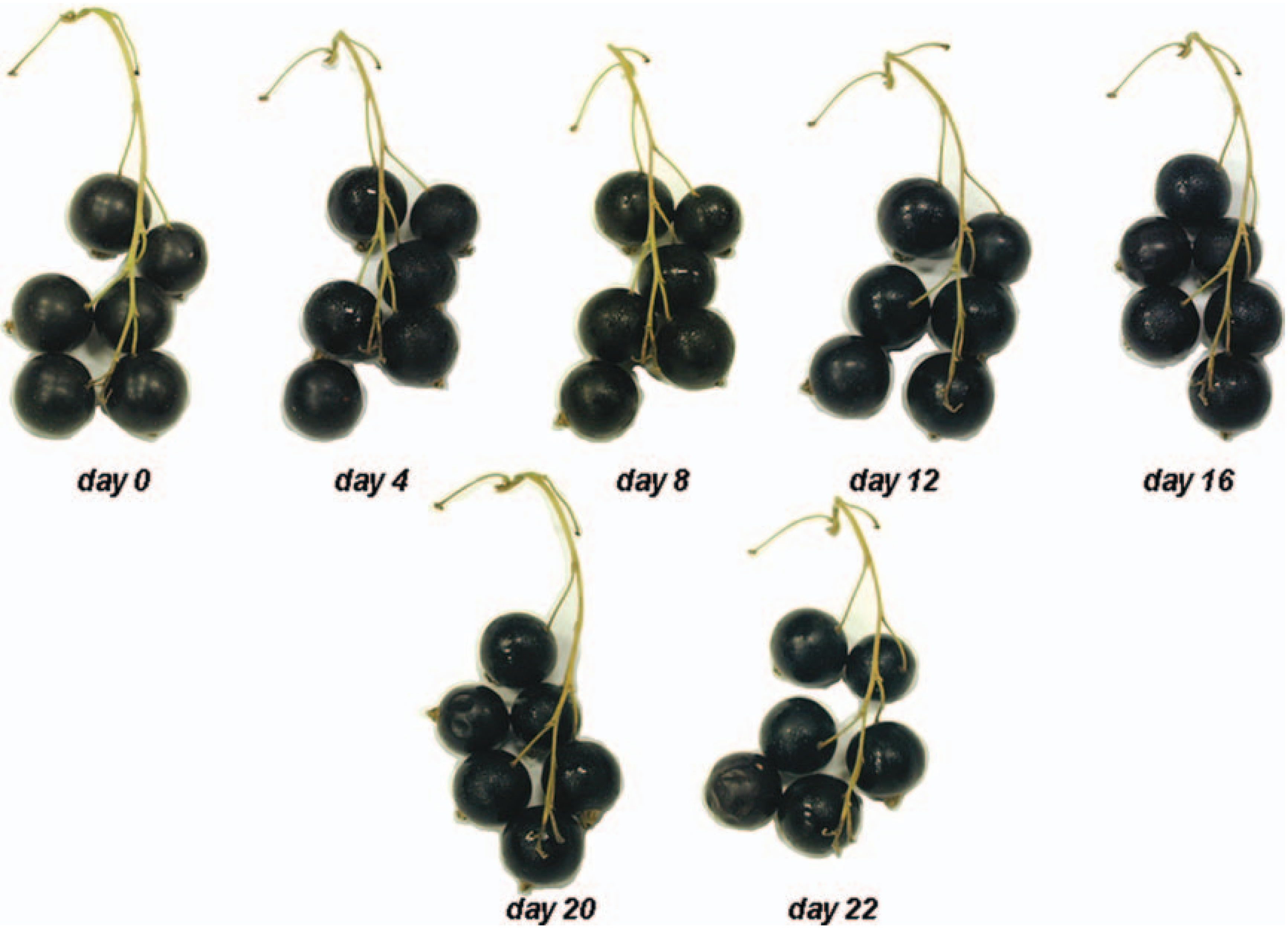
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Figure 3.12. Appearance of 'Consort' black currant stored for 22 days at 5°C. The berries maintain an acceptable appearance during 12 days, but at that time the berries start to show minor signs of shriveling and loss of glossiness. After 20 days some berries show severe signs of shriveling.

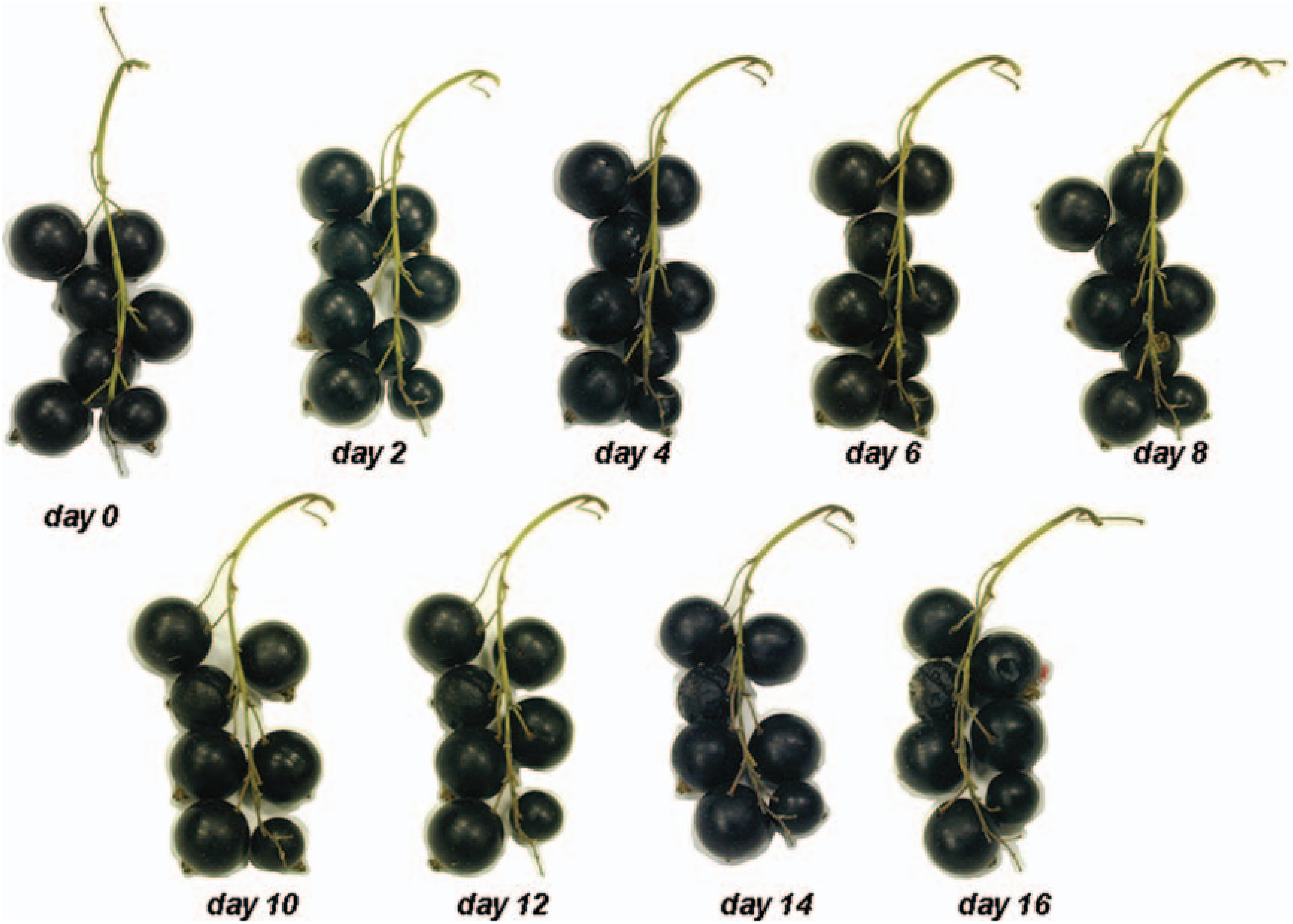
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Figure 3.13. Appearance of ‘Consort’ black currant stored for 16 days at 10°C. The berries maintain an acceptable appearance during 10 days, but at that time the berries start to show minor signs of shriveling and loss of glossiness. After 16 days some berries show severe signs of shriveling and decay.

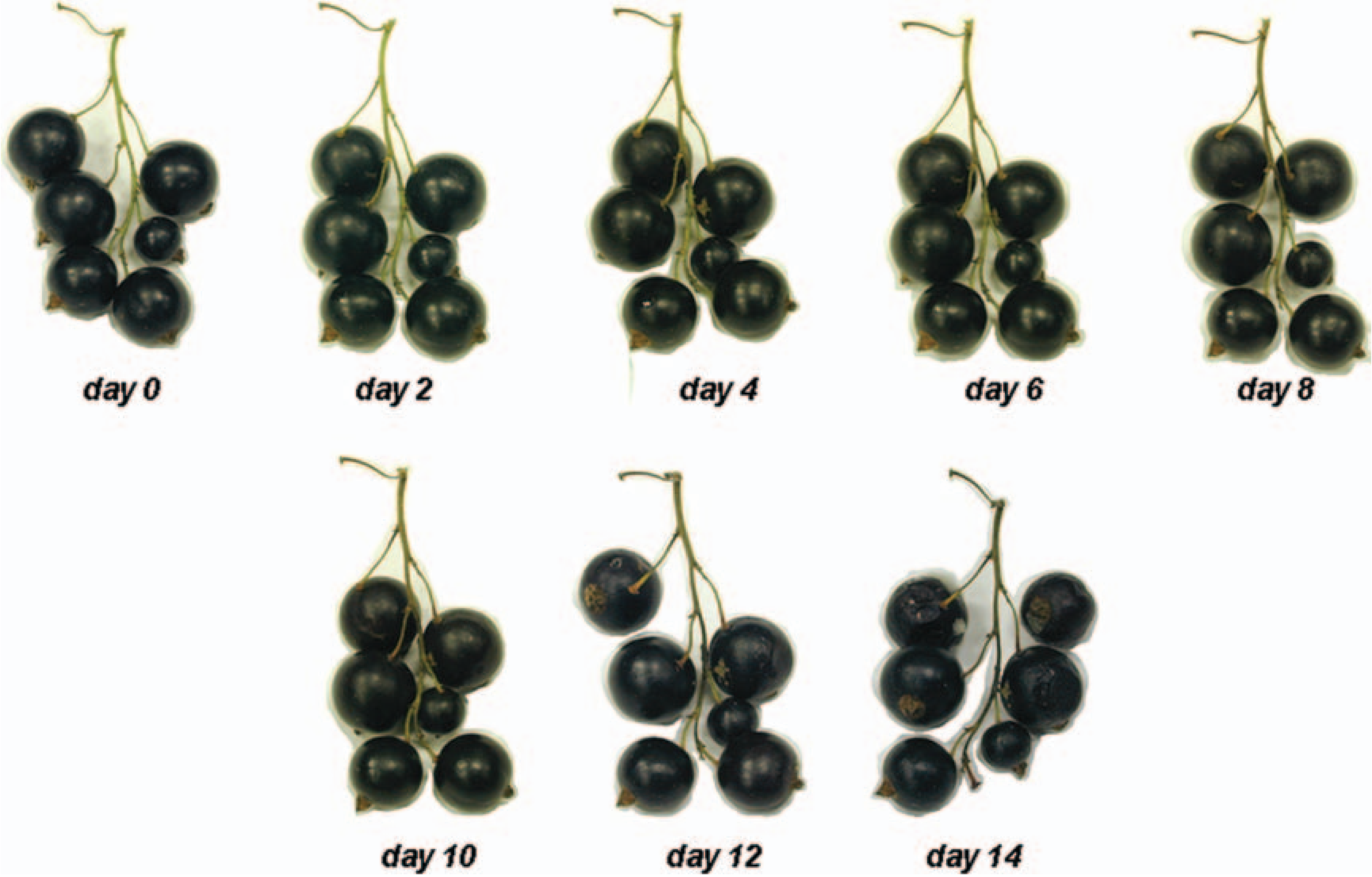
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Figure 3.14. Appearance of 'Consort' black currant stored for 14 days at 15°C. The berries maintain an acceptable appearance during 8 days, but at that time the berries start to show minor signs of shriveling and loss of glossiness. After 14 days some berries show severe signs of shriveling and decay.

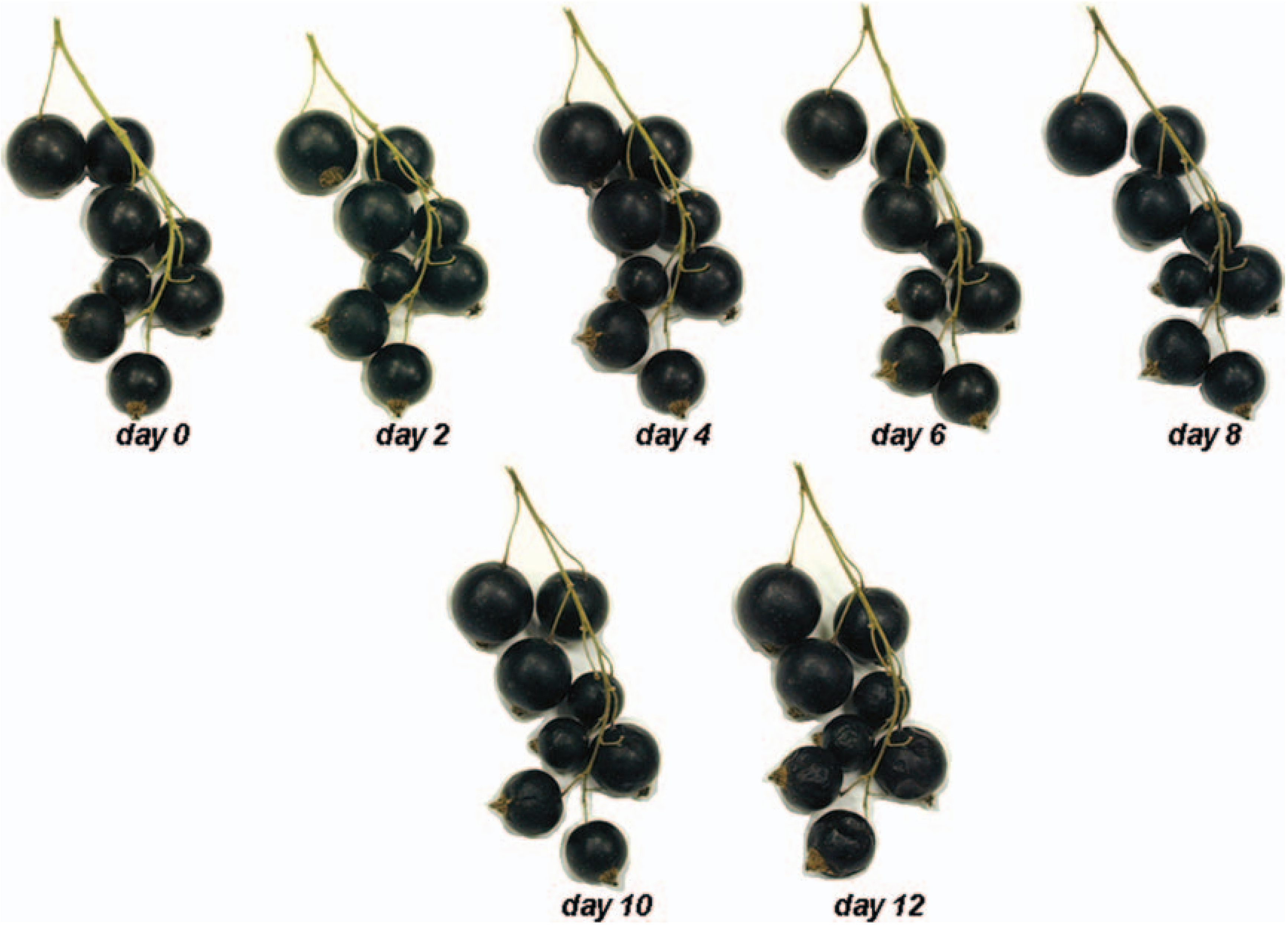
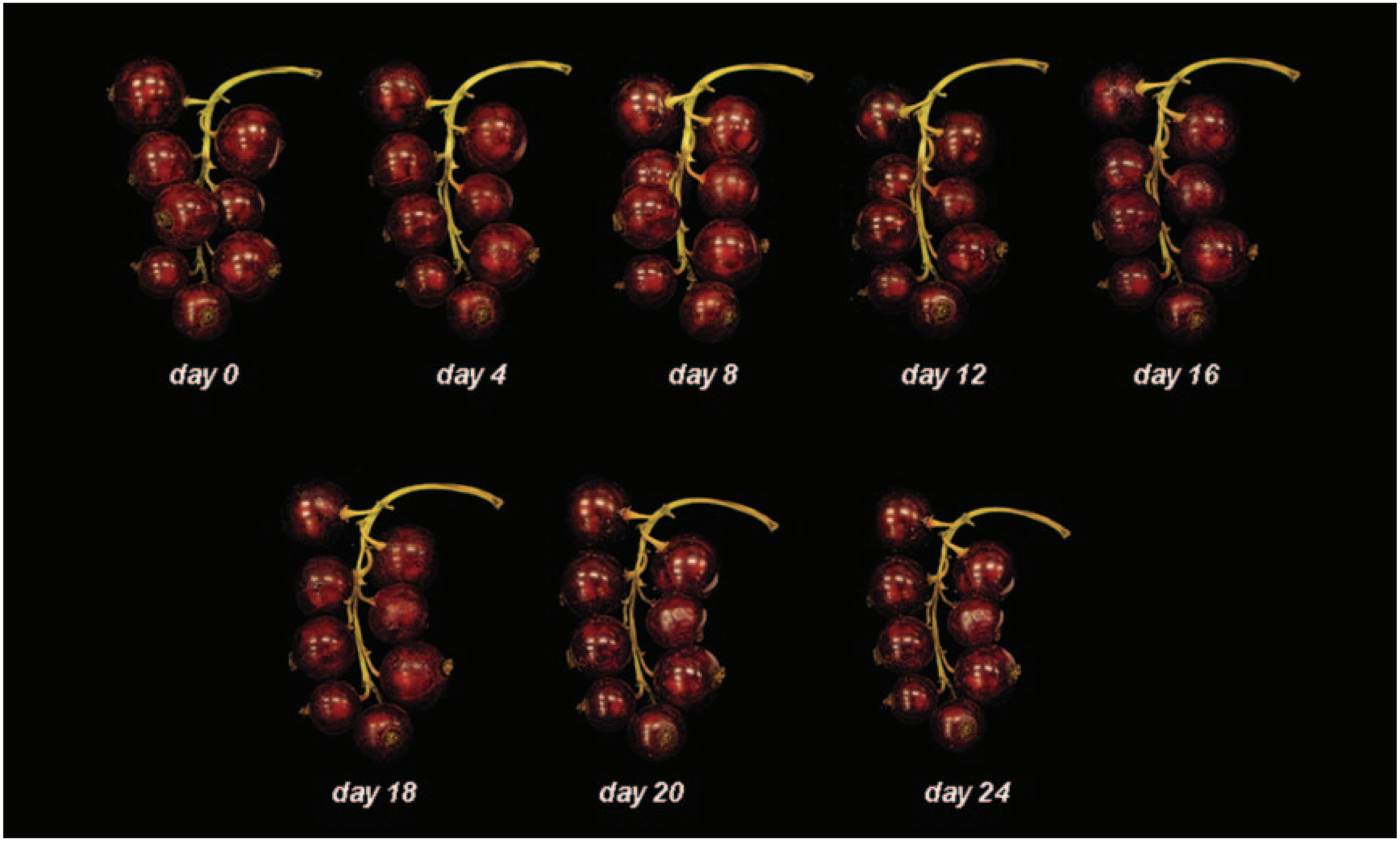


Figure 3.15. Appearance of 'Consort' black currant stored for 12 days at 20°C. The berries maintain an acceptable appearance during 6 days, but at that time the berries start to show minor signs of shriveling and loss of glossiness. After 12 days, most of the berries show severe signs of shriveling.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day 18
day 20
day 24

Figure 3.16. Appearance of 'Red Lake' red currant stored for 24 days at 0°C. The berries maintain an acceptable appearance during 16 days, but at that time the berries start to show minor signs of shriveling and loss of glossiness. After 24 days, some berries show severe signs of shriveling.

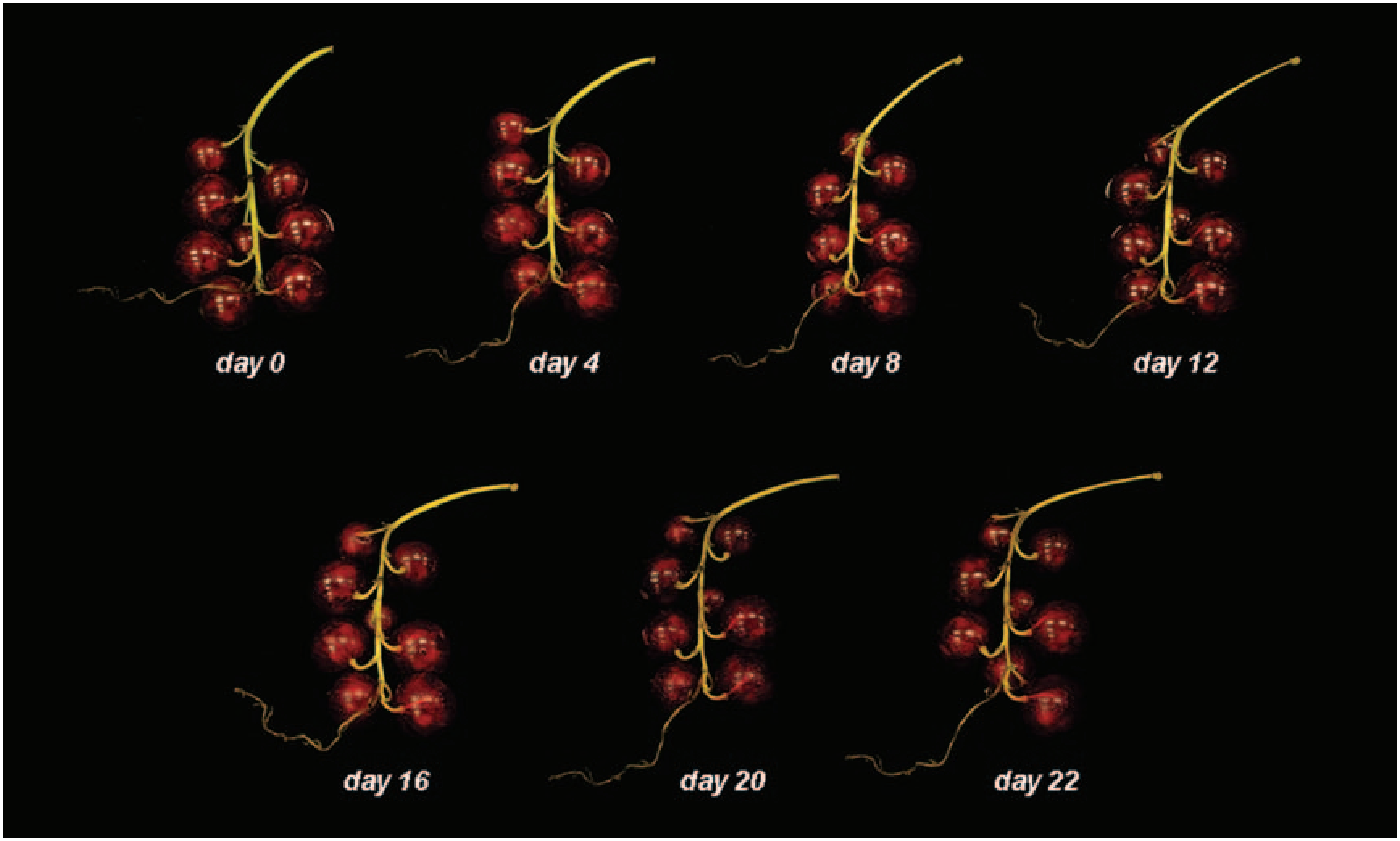
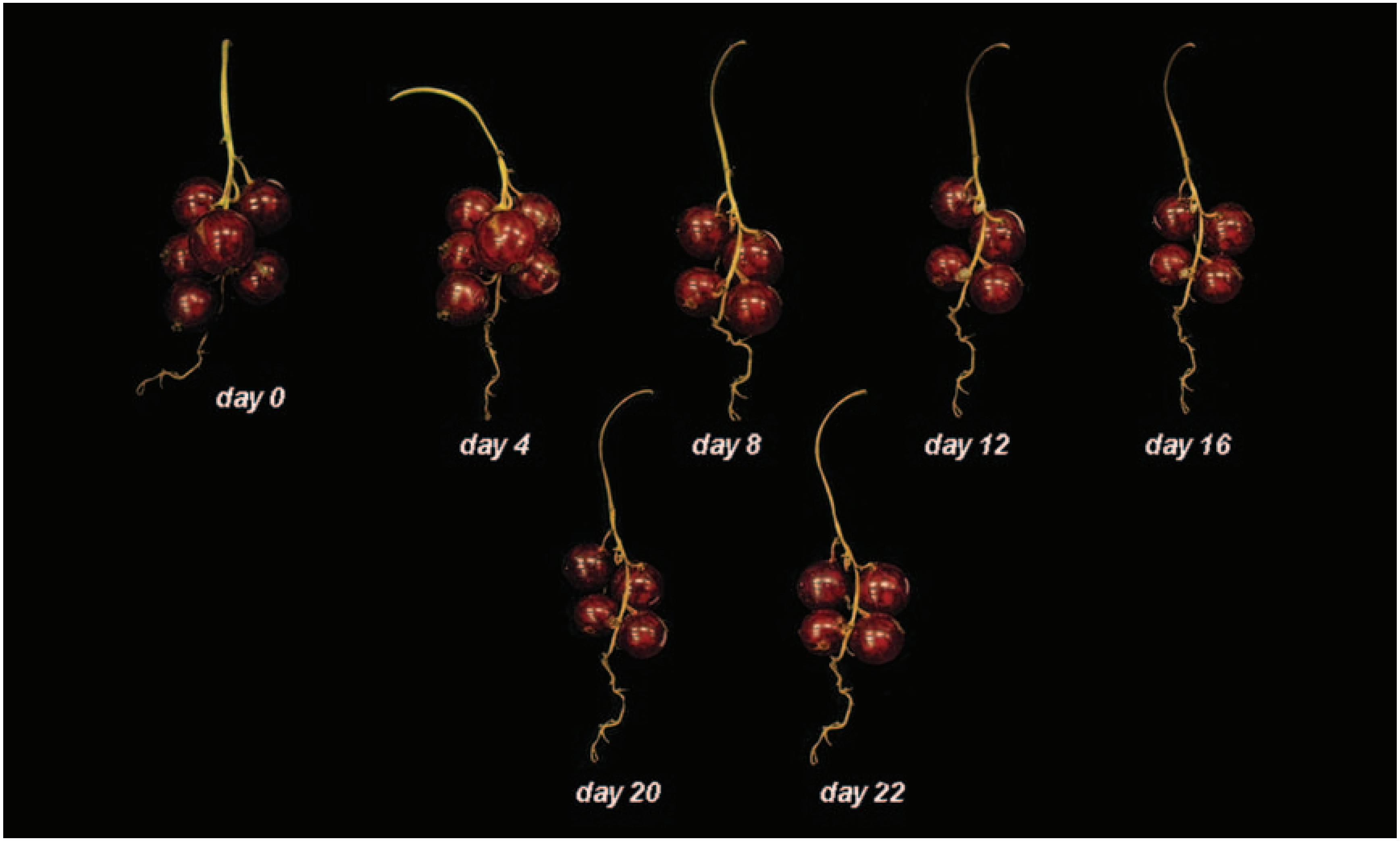


Figure 3.17. Appearance of 'Red Lake' red currant stored for 22 days at 5°C. The berries maintain an acceptable appearance during 12 days, but after that time the berries start to show minor signs of shriveling and loss of glossiness. After 22 days, the berries appear darker and less glossy and some of the berries show severe signs of shriveling.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day 22

Figure 3.18. Appearance of 'Red Lake' red currant stored for 22 days at 10°C. The berries maintain an acceptable appearance during 8 days; however, after 4 days some berries shatter due to severe decay, while the remaining berries start to show minor signs of shriveling and loss of glossiness.

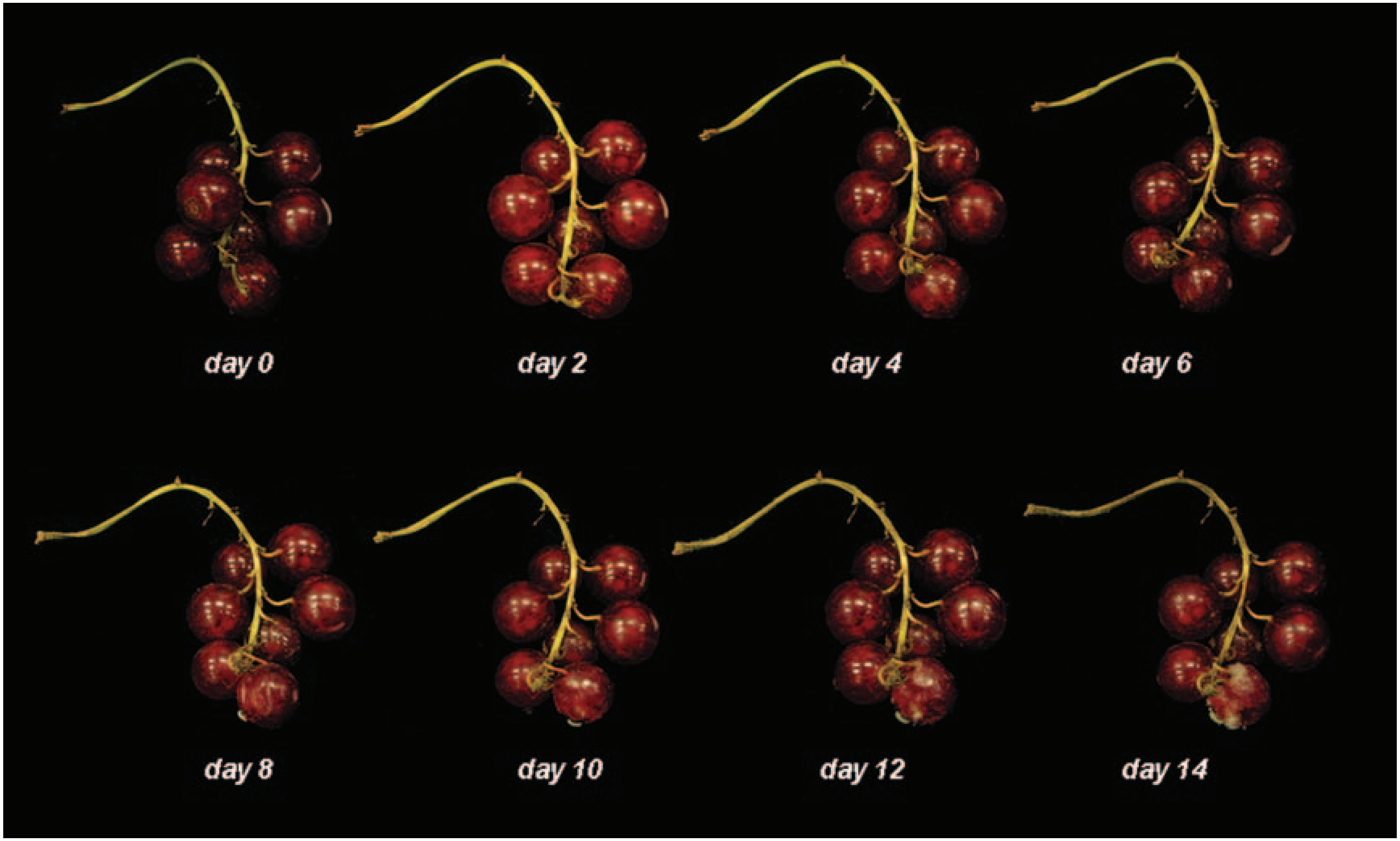
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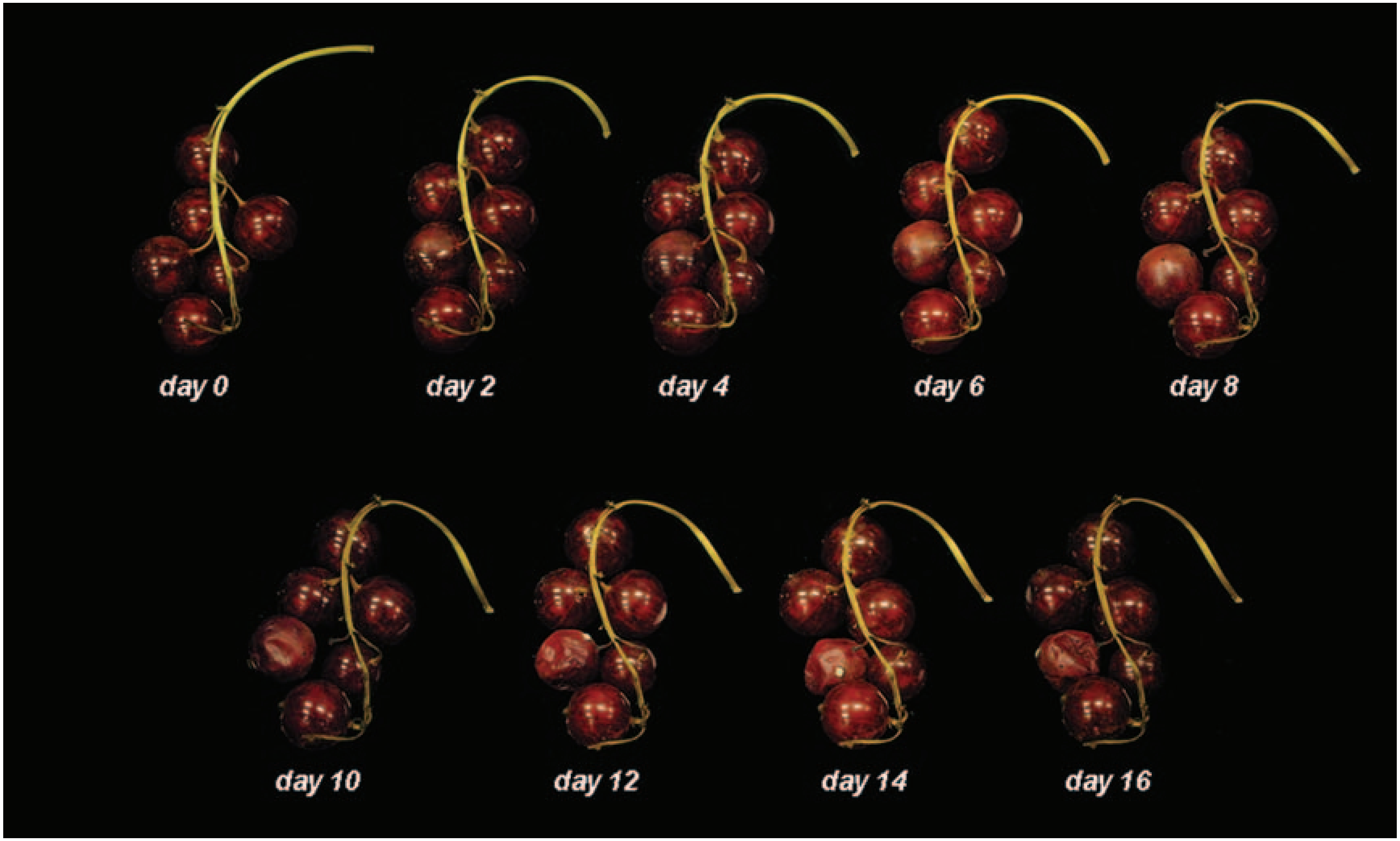
Figure 3.19. Appearance of 'Red Lake' red currant stored for 14 days at 15°C. The berries maintain an acceptable appearance during 2–4 days, but after that time berries start to show minor signs of shriveling and loss of glossiness. Decay develops after 8 days, and after 14 days some of the berries develop severe decay.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day 14
day 16

Figure 3.20. Appearance of ‘Red Lake’ red currant stored for 16 days at 20°C. The berries maintain an acceptable appearance during 2 days, but after that time berries start to show minor signs of shriveling and loss of glossiness. Some berries develop decay after 2 days, and after 14 days some of the berries are completely decayed.

RASPBERRY

Scientific Name: *Rubus idaeus*
Family: *Rosaceae*

Quality Characteristics

Raspberries are the most perishable of the soft fruits, with decay, loss of firmness, darkening of the color, and changes in flavor occurring within hours of harvest. Although ease of detachment of the fruit from the plant is the criterion most often used commercially to determine harvest maturity, to correctly evaluate raspberry quality and maturity at harvest, measures of acidity and soluble solid contents should be used simultaneously with measurement of fruit firmness and color (Kingston et al. 1991). In addition, because slightly overripe raspberries had a significantly lower suitability for selling than semi-ripe and ripe fruit (Krüger et al. 2003), it has been suggested that fruit designated for fresh market and shipping should be harvested pink and firm rather than 100% red or very ripe (Sjulin and Robbins 1987). Nonetheless, the stage of maturity of the fruit at harvest has a major effect on the eating quality of fresh raspberries. As raspberries ripen there is an increase in sweetness, fruit flavor, juiciness, and red color. Ripening stage also has a considerable effect on raspberry flavor, since with ripening the unripe-green perception decreases, whereas the fruity and flowery characteristics increase. Overall, quality acceptance of raspberries increases from the semi-ripe to the ripe stage with no further increase to overripe fruit. Therefore, raspberry acceptance is greatly dependent on sweetness, sweetness-to-acidity ratio, and fruity taste and aroma, and is negatively affected by untypical and strange taste and to a smaller extent by acidity and firmness. In addition to taste, color of raspberries can greatly influence the consumer sense of satisfaction when buying decision is based on color (Krüger et al. 2003).

During raspberry ripening, pigments change from green to red, paralleling progressive softening, loss of skin strength, and breakdown of mesocarp cell walls. During fruit development the mesocarp cells become extensively elongated, which explains the textural changes observed prior to any color changes. As the fruit turns red and soft, raspberries are easily damaged and "bleeding" caused by skin lesions is a considerable problem during postharvest handling (Sexton et al. 1997). Thus, as fruit firmness tends to decrease with increasing maturity, harvesting the fruit at a stage earlier than ripe-red would improve firmness without greatly reducing fruit weight (Sjulin and Robbins 1987).

Concurrent to decreased fruit retention strength and firmness, a decrease in acidity with increasing maturity was reported, whereas fruit weight, total anthocyanin concentration, pH, soluble solids content, and decay increase (Iannetta et al. 1999; Krüger et al. 2003; Perkins-Veazie and Nonnecke 1992; Sjulin and Robbins 1987). Citric acid is the main nonvolatile organic acid in raspberries and tends to decrease as the fruit matures (Ancos et al. 1999). Therefore, to obtain optimum flavor, shape, and color, raspberries should be harvested at or near the fully mature stage when the sugar has reached its higher content and the acidity is lower. In addition, red raspberries were reported to have the highest antioxidant activity (ORAC) at the ripe stage compared to other maturity stages (Wang and Lin 2000).

Raspberry fruit contains on average 87% water, 12% carbohydrates, 0.9% proteins, and 7% fiber, 25 mg of vitamin C, and minor amounts of other vitamins per 100 g of fresh fruit (USDA 2006). Raspberries are among the fruits containing the highest antioxidant levels. In addition to vitamin C, raspberries contain numerous phenolic compounds (anthocyanins, flavonols, hydroxycinnamic acids, benzoic acids, ellagitannins, and procyanidins) with beneficial health benefits (Anttonen and Karjalainen 2005; Kähkönen et al. 2001). Concentration of phenolic compounds is usually higher in less-ripe raspberries than in mature fruits, with the exception of anthocyanins, which generally accumulate during the maturation of red fruits (Beekwilder et al. 2005; Moore 1997; Sjulin and Robbins 1987). Although total phenolic content of red raspberries showed a decrease from the green to the pink stages, a significant increase was reported from the pink to the ripe stages (Wang and Lin 2000). Raspberries darken as they ripen (Krüger et al. 2003; Perkins-Veazie and Nonnecke 1992; Robbins and Moore, 1990), and changes in the fruit color from orange-red to red or purple-red during ripening have been attributed to an increase in anthocyanin synthesis (Moore 1997; Sjulin and Robbins 1987). During ripening, some anthocyanins are synthesized, whereas others, such as cyanidin-3-glucoside, are present early in fruit development (Beekwilder et al. 2005). Anthocyanins, with the exception of cyanidin-3-glucoside, which is already present in unripe fruit, accumulate only when the fruit is red and still attached to the torus or receptacle, or when the fruit is red ripe and easily detached from the receptacle. In contrast, other polyphenols such as ellagitannins are initially present in high levels in unripe fruit but decrease as the raspberry matures (Beekwilder et al. 2005).

Optimum Postharvest Handling Conditions

Because of its delicate structure and rapid deterioration raspberry fruit has a very short postharvest life. To extend the postharvest life and maintain fruit quality, raspberries should be forced-air pre-cooled to 1°C promptly after harvest. Delaying the pre-cooling of raspberries from 0.5 to 12 hours after harvest resulted in greater weight loss, increased fruit softening, and darker, less red and more bluish-red colored fruit during subsequent storage for 8 days at 0°C (Moore and Robbins 1992). After pre-cooling, fruits should be maintained throughout the postharvest handling at temperatures between −0.5 and 0°C with 90–95% relative humidity. Under these conditions, a postharvest life of 2–5 days, depending on the cultivar and maturity at harvest, should be expected (Perkins-Veazie 2004c).

Temperature Effects on Quality

Raspberries are a highly perishable fruit and their postharvest life can be greatly reduced if the fruit is held at temperatures above 0°C (Salunke and Desai 1984). However, even when raspberries are stored at optimum temperature, their postharvest life can be as short as 2–3 days (Hardenburg et al. 1986). In many cultivars, raspberry color darkens during storage, with fruit appearing more bluish-red after 16 days at 0 and 20°C. Color changes are dependent on the storage temperature, with color changing faster in fruit stored at 20°C than in those stored at 0 or 4.5°C (Robbins and Moore 1990). Compared to other raspberry cultivars (i.e., 'Heritage'), 'Killarney' was classified as the lightest (higher L* value), less red, and with the highest chroma values (Riaz and Bushway 1996). The L* value of 'Killarney' raspberries decreased regardless of the storage temperature, meaning that the fruit loses the bright red color during storage, becoming darker. In fact, the color changed from a bright orangish-red to a darker red (decrease in L* and hue angle), and at the end of storage the raspberries were more red-purplish than red when compared with freshly harvested fruit. The hue angle of fruit stored at higher temperatures decreased faster than that stored at 0°C. Chroma of raspberries decreased during storage, but the decrease was more evident in raspberries stored at temperatures above 5°C. During storage, the color of the fruit became less vivid than at the time of harvest (lower chroma), but the lower temperatures tended to better maintain the red color of the fruit (Nunes et al. 2003a). Raspberries exposed to simulated harvest-to-consumer conditions (i.e., 1 day at 20°C and 3 days at 2–4°C and 85–90% relative humidity followed by 1 day at 20°C) had lower L* value, hue, and chroma values and thus were less red and more blue than at harvest (Krüger et al. 2003). Robbins and Moore (1990) also reported that L*, a*, and b* values of several raspberry cultivars decreased with increasing storage time. When stored at 10°C for 10 days, L*, a*, and b* values of 'Heritage' raspberries decreased significantly (Wang 2003). In general, color of raspberries changes from an orangish-red to a bluish-red when fruit ripens or with increasing storage time and temperature (Perkins-Veazie and Nonnecke 1992; Robbins and Moore 1990).

Raspberry fruit firmness, measured as compression of the opening, decreases during storage, and the rate of softening, is greatly related to the postharvest temperature (Callesen and Holm 1989; Chanjirakul et al. 2006; Krüger et al. 2003; Nunes et al. 2003a; Varseveld and Richardson 1980). 'Killarney' raspberries softened during storage, with the rate of softening increasing with storage temperature. Firmness of 'Killarney' raspberries stored at 0°C was considered unacceptable after approximately 4–6 days, whereas at 5°C fruit softened faster and reached an objectionable level of firmness after 3 days (Nunes et al. 2003a). Similarly, 'Meeker' raspberries stored at 5°C were extremely soft after 7 or 8 days of storage (Varseveld and Richardson 1980). 'Killarney' raspberries stored at 15°C were soft and leaky after 2 days, and after 1–2 days at 20°C softening was considered unacceptable (Nunes et al. 2003a). Likewise, raspberries exposed to simulated harvest-to-consumer conditions (i.e., 1 day at 20°C then 3 days at 2–4°C, 85–90% relative humidity, followed by 1 day at 20°C) softened, with riper fruit softening more and faster (Krüger et al. 2003). Raspberries stored at 25°C became extremely soft after 2 days, whereas fruit stored at 15°C attained the same degree of softness after 4 days (Varseveld and Richardson 1980).

Decay also increases with increased storage time and temperature (Sjulin and Robbins 1987). After 14 days, 100% of the raspberries stored at 10°C had decay (Chanjirakul et al. 2006), whereas 'Meeker' raspberries stored for 4 days at 5, 15, and 25°C had mold counts of 1, 68, and 100%, respectively (Varseveld and Richardson 1980). In another study, approximately 60% of raspberry fruit stored at 5°C and 95–100% relative humidity developed decay after 12 days (Callesen and Holm 1989), probably owing to high humidity levels during storage.

When raspberries were harvested at the pink stage and stored under simulated harvest-to-consumer condition (i.e., 1 day at 20°C and 3 days at 2–4°C, with 85–90% relative humidity, followed by 1 day at 20°C), characteristic unripe and green aroma were replaced by fruity and flowery aroma with increasing storage time (Krüger et al. 2003). However, loss of fruity aroma was rapid in the 'Killarney' raspberries stored at 15 and 20°C. Although fruits stored at 0°C maintained an acceptable aroma during 5–6 days, the aroma of the fruit stored at 15 and 20°C was considered unacceptable due to off-flavors after 1 or 2 days. Loss of taste followed the same pattern as loss of aroma for fruit stored at 15 and 20°C, but loss of taste was faster than loss of aroma in fruits stored at lower temperatures. In fruits stored at 0 and 5°C the taste was no longer acceptable after 4–7 days of storage (Nunes et al. 2003a).

The maximum acceptable weight loss before raspberries became unacceptable for sale was considered to be 6% (Robinson et al. 1975). After 5, 4, and 3 days at 10, 15, and 20°C, respectively, 'Killarney' raspberries had lost less than 6% of their initial weight, and raspberries stored at 0 or 5°C reached the maximum acceptable weight loss after approximately 6 days (Nunes et al. 2003a). 'Meeker' and 'Willamette' red raspberries stored at 5, 15, and 25°C had weight losses of 0.6, 3.1, and 5% after 4 days of storage. Weight loss increased rapidly after storage for 2 days at 25°C, 3 days at 15°C, and 4 days at 5°C, when decay became apparent (Varseveld and Richardson 1980). Other raspberry cultivars stored at 1.7 or 5°C and 95–100% relative humidity lost only 1% of their initial weight after 7 or 11 days (Callesen and Holm 1989). However, weight loss of raspberries exposed to simulated harvest-to-consumer conditions (i.e., 1 day at 20°C and 3 days at 2–4°C and 85–90% relative humidity followed by 1 day at 20°C) was about 10% and was mostly affected by the last 24 hours at 20°C, whereas the additional 3 days at 2°C caused smaller losses (Krüger et al. 2003). Weight loss, and the consequent visual signs of shriveling, is not a critical quality-limiting factor if the fruit is maintained in an environment with humidity around 95–100% (Callesen and Holm 1989; Nunes et al. 2003a).

Changes in the visual quality attributes of raspberries due to temperature usually overlap changes in the composition of the fruit. Therefore, during storage at 0 or 1°C the color of raspberries darkens, and soluble solids content, pH, and total anthocyanin concentration increase and acid content decreases (Haffner et al. 2002; Krüger et al. 2003; Robbins et al. 1989; Sjulin and Robbins 1987). Storage of 'Meeker' raspberries for 9 days at 0°C resulted in increased pH and total anthocyanin concentration and decreased acidity (Krüger et al. 2003). Holding raspberries at 5°C for 12 days decreased total acid and also decreased the ascorbic acid content (Callesen and Holm 1989). In 'Willamette' and 'Meeker' red raspberries, soluble solids content increased throughout storage at 5, 15, or 20°C, and then decreased gradually, whereas total acidity declined in a linear manner and pH values remained essentially unchanged (Varseveld and Richardson 1980).

Darkening of raspberries usually results from an increase in total anthocyanin concentration during storage (Kalt et al. 1999; Robbins et al. 1989; Sjulin and Robbins 1987). The degree of increase differs with storage time and temperature and with cultivar. Anthocyanin content of 'Meeker' red ripe raspberries held at 0°C increased by about 70% between harvest and 24 days of storage and then remained unchanged (Robbins et al. 1989). However, when stored for 7 or 10 days at 10°C, total phenolic and anthocyanin contents and antioxidant activity (ORAC) decreased compared to initial values at harvest (Chanjirakul et al. 2006). Other studies have shown, however, that after 8 days at 20°C anthocyanin and phenolic contents increased by about 1.5- and 2.5-fold, respectively, whereas changes were less after storage at 10 and 30°C and least at 0°C. The increase in raspberry phenolic and anthocyanin contents contributes to an increase in the antioxidant capacity of the fruit. Antioxidant capacity (ORAC) of 'Heritage' raspberries stored at 1°C for 10 days significantly increased during storage (Wang 2003).

Temperature also has a major effect on the ascorbic acid content of fresh raspberries. For example, after 7 or 14 days at 10°C ascorbate and dehydroascorbate contents of raspberries significantly decreased compared to values at harvest (Chanjirakul et al. 2006). Furthermore, after 8 days at 20°C ascorbic acid content decreased by 22%, whereas 46% of the ascorbic acid content was lost at 30°C (Kalt et al. 1999). When stored for 9 days at 1°C and then held for 1 day at 18°C, the total ascorbic acid content of raspberries was reduced by 90% compared to initial values (Agar et al. 1997). In contrast, when stored for 3 weeks at 2°C and 95–100% humidity, raspberries retained 86% of their initial ascorbic acid content (Albrecht et al. 1991).

Time and Temperature Effects on the Visual Quality of 'Killarney' Raspberries

'Killarney' raspberries shown in Figures 3.21–3.25 were harvested at the fully ripe stage, when easily detached from the plant, from a commercial operation in Saint-Nicolas, Quebec, Canada, during the summer season (i.e., July). Promptly after harvest, fresh raspberries were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

'Killarney' raspberries change from a light orangish-red to a dark purplish-red during storage, especially if the fruit is held at temperatures higher than 0°C. Raspberries stored at 0°C for 5 days maintain an acceptable bright red color, then appear more dark red after 7 days, but are still visually acceptable (Figure 3.21).

Raspberries stored at 5°C maintain an acceptable red color for 3 or 4 days of storage; then the fruit develops a very dark red color and appears overripe. Visible mold appears after 5 days, and fruit appears extremely overripe, soft, and decayed after 7 days (Figure 3.22).

Fruit stored at 10°C changes rapidly in color compared to fruit stored at 0 or 5°C. After 4 days, raspberries change from light to dark red and continue to darken with storage. After 7 days the fruit appears very dark brownish-red and overripe, and visible decay is present on the fruit surface after 6 days (Figure 3.23).

When raspberries are stored at 15°C, decay develops rapidly and before visible color changes. After 3 days, raspberries are still bright red but mold growth is evident on the fruit surface. After 7 days the fruit is completely covered with gray mold (Figure 3.24).

Development of decay is even faster in raspberries stored at 20°C compared to 15°C, and after only 2 days a slight brownish sunken depression affecting some of the drupelets is already perceptible at the equatorial part of the fruit. As storage time progresses, decay spreads extremely quickly to the rest of the fruit surface, and after 7 days the fruit is completely covered with mold (Figure 3.25).

Overall, raspberry color changes (bright orangish-red to a dark red or dark brownish-red) and visible decay are the two major changes in raspberry visual quality during storage. The changes occur rapidly and are more pronounced with increasing storage temperature. 'Killarney' raspberries stored at 0°C maintain a better visual quality for longer periods (6–7 days), when compared to fruit stored at higher temperatures. Raspberries stored at 5, 10, 15, and 20°C maintain acceptable visual quality during 4, 3, 2, and 1 day, respectively. After that time the visual quality of the fruit deteriorates rapidly.

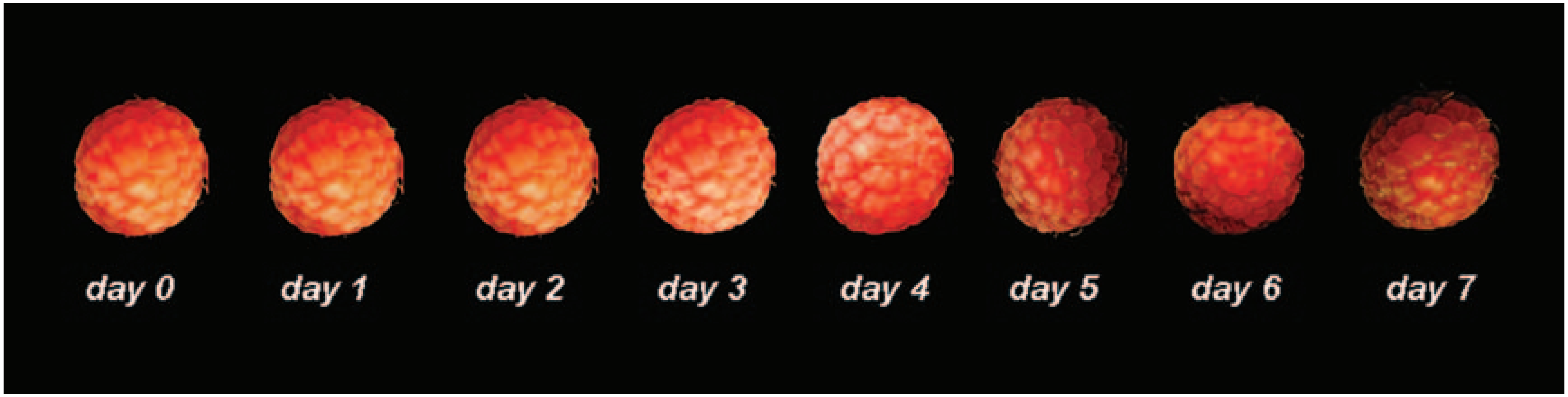

day 0
day 1
day 2
day 3
day 4
day 5
day 6
day 7

Figure 3.21. Appearance of 'Killarney' raspberry stored for 7 days at 0°C. Fruit maintains an acceptable appearance during 6 days. After 4 days the color of the fruit darkens, and after 7 days the raspberry appears more red and dull.

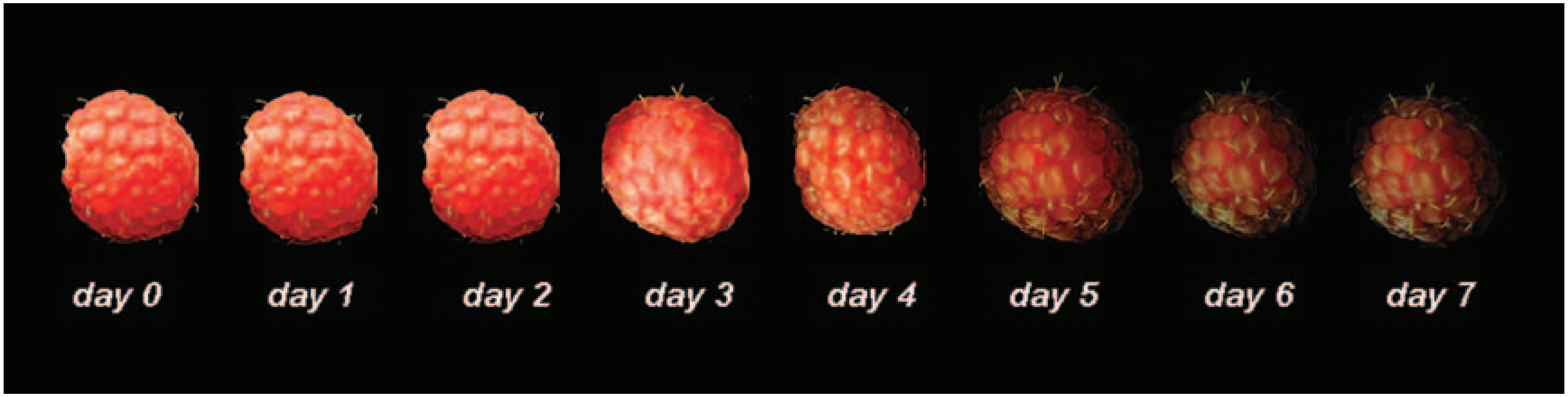

day 0
day 1
day 2
day 3
day 4
day 5
day 6
day 7

Figure 3.22. Appearance of 'Killarney' raspberry stored for 7 days at 5°C. Fruit maintains an acceptable appearance during 4 days. After 4 days the color of the fruit darkens, and after 7 days the raspberry appears very dark red, dull, and overripe.

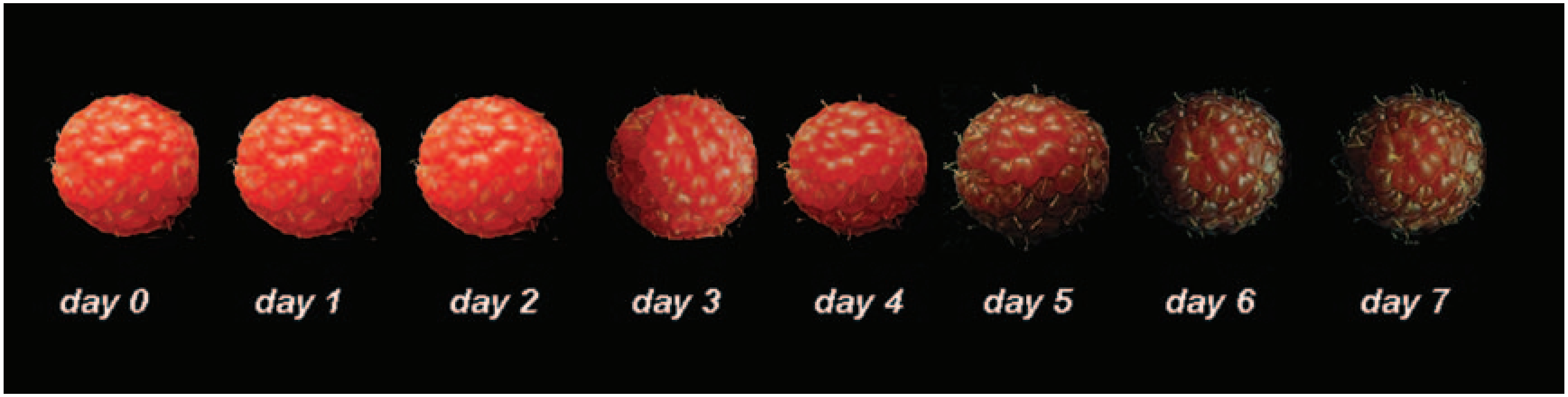

day 0
day 1
day 2
day 3
day 4
day 5
day 6
day 7

Figure 3.23. Appearance of 'Killarney' raspberry stored for 7 days at 10°C. Fruit maintains an acceptable appearance during 3 days. After 3 days the color of the fruit darkens, and after 5 days the color is very dark red and dull, and the raspberry appears overripe.

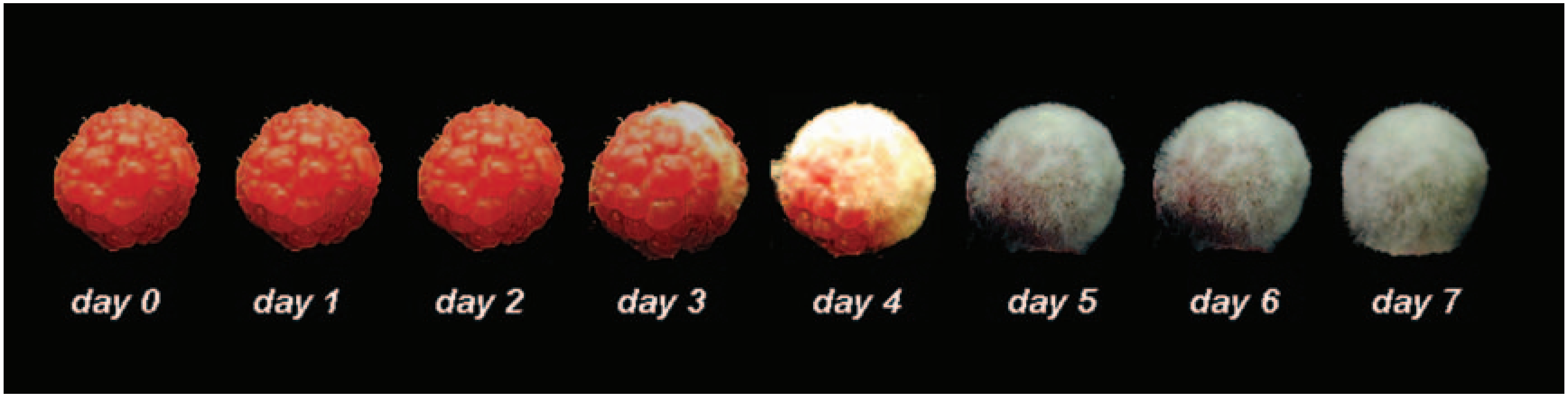

day 0
day 1
day 2
day 3
day 4
day 5
day 6
day 7

Figure 3.24. Appearance of 'Killarney' raspberry stored for 7 days at 15°C. Fruit maintains an acceptable appearance during 2 days. After 2 days decay starts to develop, and after 7 days the raspberry is completely covered with mold.

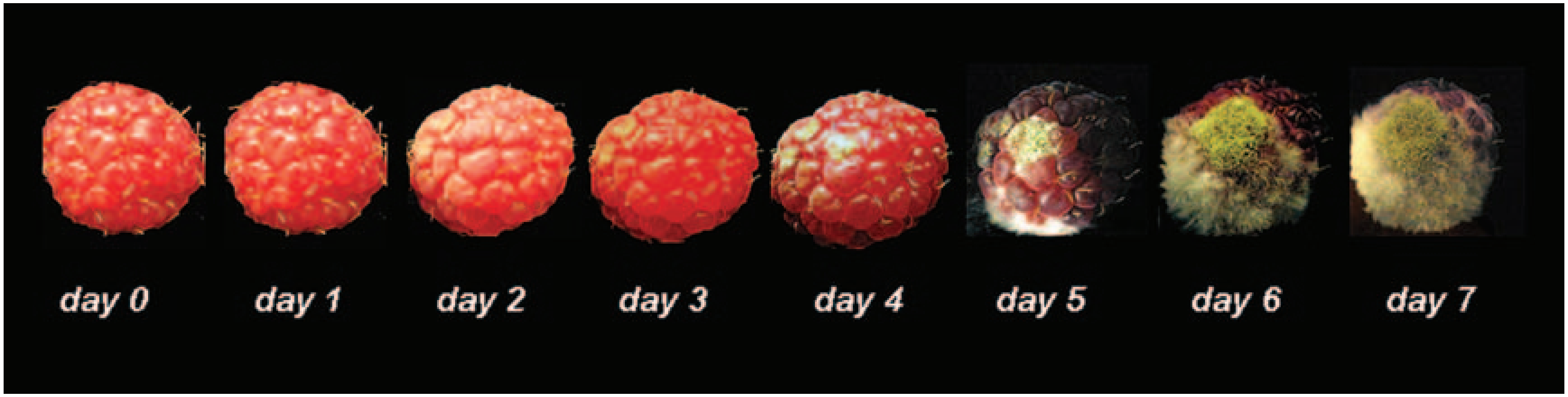

day 0
day 1
day 2
day 3
day 4
day 5
day 6
day 7

Figure 3.25. Appearance of 'Killarney' raspberry stored for 7 days at 20°C. Fruit maintains an acceptable appearance during 1 day. After 1 day the fruit develops severe shriveling and appears dry; decay develops after 2 days, and after 7 days the raspberry is completely covered with mold.

STRAWBERRY

Scientific Name: *Fragaria spp.*
Family: Rosaceae

Quality Characteristics

Quality of strawberries is based primarily on color, texture, and fruit flavor. For best eating quality, strawberries should be harvested at or near the full ripe stage, as immature fruit has poor eating quality (low sugars, little juice, and odd texture) (Kader 1990; Nunes et al. 2006). Although soluble solids, acidity and anthocyanin contents, and red color may continue to increase in strawberry fruit during storage, fruit that is harvested before the three-quarters-colored stage will not reach the same visual, eating, and compositional levels as fruit harvested at the proper maturity stage (Nunes et al. 2006). Ripening increases simple sugars that contribute to sweetness, decreases the organic acids and phenolics that cause acidity and astringency, and increases the aroma volatiles that yield the characteristic strawberry flavor of the fruit. As ripening proceeds, degradation of vitamins, proteins, lipids, and other carbohydrates also occurs (Salunkhe et al. 1991). As strawberry fruit matures, firmness decreases. Ménager et al. (2004) found that strawberry firmness decreased from white to half-red and then appeared to stabilize from the three-quarters to the full and dark red stages. At harvest, firmness of half-red strawberries was 20% higher than the firmness of full-red or dark red strawberries (Forney et al. 1998; Ménager et al. 2004; Nunes et al. 2006). Softening of strawberry fruit, either during ripening in the field or during storage, is mainly the result of loss of cell wall material, which is more pronounced in the cortical tissue than in the pith tissue (Koh and Melton 2002). In addition, the extreme fragility of ripe strawberry fruit results from its particular structure, characterized by large cells and thin cell walls (Szczesniak and Smith 1969).

The major sugars in strawberry fruit are sucrose, glucose, and fructose, accounting for more than 99% of the total sugars in ripe fruit (Strum et al. 2003; Wroldstad and Shallenberger 1981). During ripening the content of sucrose decreases while the content of glucose and fructose increases (Ferreyra et al. 2007; Montero et al. 1996; Strum et al. 2003). However, a great variation in sugar content of strawberries can be found owing to environmental differences as well as cultivar characteristics (Haila et al. 1992; Shamaila et al. 1992; Strum et al. 2003; Wroldstad and Shallenberger 1981). The soluble solids and total sugars content of strawberries tends to increase as the fruit matures (Knee et al. 1977; Ménager et al. 2004; Nunes et al. 2006; Spayd and Morris 1981b; Strum et al. 2003; Woodward 1972). When compared to half-ripe or ripe fruit, a slight decrease in soluble solids content in overripe fruit may occur (Reyes et al. 1982). The maximum content of soluble solids was seen after approximately 28 days from fruit set, decreasing significantly from that point forward (Montero et al. 1996).

The primary organic acids in strawberry fruit are citric and malic acids, which are important flavor components. Citric acid accounts for approximately 90% of the total acid contents in strawberry fruit (Haila et al. 1992; Reyes at al. 1982; Strum et al. 2003). Acidity increases slightly to a maximum in mature green fruit and then declines rapidly in the later stages of fruit ripening (Forney et al. 1998; Moing et al. 2001; Montero et al. 1996; Nunes et al. 2006; Spayd and Morris 1981a; Strum et al. 2003). Strawberry pH decreases during ripening from green to red, and then remains unchanged (Moing et al. 2001). In general, a minimum of 7% soluble solids content and a maximum of 0.8% titratable acidity are recommended for a strawberry fruit with acceptable flavor (Mitcham at al. 2007).

Anthocyanins, carotenoids, and chlorophyll are the main pigments responsible for the color of strawberry fruit (Cheng and Breen 1991; Given et al. 1988; Gross 1982; Spayd and Morris 1981a; Woodward 1972). As strawberry fruit ripens, the anthocyanin content increases, whereas the chlorophyll content decreases (Given et al. 1988; Cordenunsi et al. 2002; Ferreyra et al. 2007; Ihl et al. 1999; Kosar et al. 2004; Montero et al. 1996; Nunes et al. 2006; Woodward 1972). The main anthocyanins of strawberry fruit are pelargonidin-3-glucoside (80%) and cyanidin-3-glucoside (Bakker et al. 1994). The cyanidin aglycon is thought to impart the orange-red color of the fruit, and pelargonidin the orange color (Mazza and Miniati 1993). Consequently, differences in color among strawberry cultivars and fruit maturity are due to different concentrations of these two pigments. A mean increase of about 31% in the total anthocyanin content of strawberries was observed from the three-quarters to the full-red colored stage for strawberries ripened in the field. Cyanidin-3-glucoside and pelargonidin-3-glucoside contents increased by 28 and 30%, respectively, from the three-quarters to the full-red colored stage in three different strawberry cultivars ('Oso Grande,' 'Chandler,' and 'Sweet Charlie') ripened in the field (Nunes et al. 2006).

Strawberries are an excellent source of vitamin C, since they contain on average 40–90 mg of vitamin C per 100 g. This means that with a supply of 100 g of strawberries (five to ten fruits), daily needs of vitamin C will be covered (Lundergan and Moore 1975; McCance and Widdowson 1978). Total ascorbic acid content increases during development and ripening of the strawberries (Cordenunsi et al. 2002; Montero et al. 1996; Nunes et al. 2006; Olsson et al. 2004; Spayd and Morris 1981b), with the most significant gain in ascorbic acid found as half-colored 'Chandler' changed to full-red colored, and as three-quarters-colored 'Oso Grande' changed to full-red color (Nunes et al. 2006). Ascorbic acid content in green fruits was half of the amount found in ripe fruits, and green strawberries had only 20% of the ascorbic acid content found in the ripe fruits (Burkhart and Lineberry 1942). Strawberry fruit contains on average 92% water, 7% carbohydrates, 0.6% proteins, 2% fiber, 40–90 mg of vitamin C, and smaller amounts of other vitamins per 100 g of fresh fruit (Lundergan and Moore 1975; McCance and Widdowson 1978; USDA 2006).

Optimum Postharvest Handling Conditions

Strawberries are a highly perishable fruit, with storage temperatures higher than 0°C greatly reducing postharvest life. Even at the optimum storage temperature, the postharvest life of strawberries can be as short as 5–7 days (Hardenburg et al. 1986; Mitcham 2004). When the temperature of the fruits is raised from 0 to 10°C, the rate of deterioration increased by 2- to 4-fold, and when strawberries were held at 29.4°C for different periods after harvest before pre-cooling, a very rapid reduction in the amount of marketable fruits was observed (Mitchell et al. 1996). Therefore, to reduce decay and loss of quality during storage, strawberries should be pre-cooled immediately after harvest or not more than 2 or 3 hours after harvest (Mitchell et al. 1996; Nunes et al. 1995a, 1995b, 2005a). Because strawberries are not sensitive to low temperatures, they can be safely cooled to a temperature of 0–1°C, and that temperature should be maintained during all subsequent postharvest periods (Hardenburg et al. 1986). To avoid water loss as well as condensation on the fruit surface, the relative humidity of the storage environment for strawberries should be maintained in a range of 90–95%. In addition, strawberries should be cooled prior to packaging, and fluctuations in the storage temperature should be prevented to avoid moisture condensation on the fruits, which favors the growth of surface mold and development of decay (Boyette et al. 1989; Goulart 1993; Hardenburg et al. 1986).

Temperature Effects on Quality

Changes in the visual, eating, and compositional quality of strawberry fruit occur rapidly after harvest and are greatly governed by temperature. The strawberry color changes during storage, mainly with storage time and temperature (Sistrunk and Morris 1978). Color degradation from dark red to brownish-red that sometimes occurs during storage of strawberries is accompanied by a decrease in red-pigmented anthocyanin and by an increase in red-brown pigments, from either enzymatic or nonenzymatic reactions during storage (Bakker et al. 1992; Skrede et al. 1992; Wroldstad et al. 1990). The loss of color may take place rapidly due to the great instability of pelargonidin-3-glucoside, the principal pigment of strawberries (Cash and Sistrunk 1970). Development of strawberry surface-browning was attributed to anthocyanin degradation and oxidation of soluble phenolic compounds, caused by a possible increase in the polyphenoloxidase activity as a result of water loss (Nunes et al. 2005b).

The rate of color loss in strawberries may increase by two to three times for each 5°C rise in storage temperature above 0°C, and the fruit color becomes brownish-red (Collins and Perkins-Veazie 1993). The calyx of the strawberries usually loses water and darkens during storage, regardless of the storage temperature, and some browning may occur, especially in the crown of the calyx at the point of the pedicel attachment (Collins and Perkins-Veazie 1993). Kalt et al. (1993) harvested strawberries at different stages of color development and after 8 days of storage at 5, 10, 20, and 30°C noticed that anthocyanin formation and changes in surface color of white-harvested strawberries were temperature- and storage-time dependent. At 5 or 10°C, an increase in anthocyanin content occurred, at 20°C pigments accumulated rapidly, but at 30°C anthocyanin synthesis was slower than at 20°C. Therefore, anthocyanin content increases at certain temperatures, possibly owing to synthesis of the pigments, but at temperatures above 30°C, degradation might occur. After 8 days at 5 or 10°C, unripe strawberries were still not completely red, whereas full-red strawberries were dark red with an overripe appearance (Kalt et al. 1993). Total anthocyanin content in strawberries harvested three-quarters colored increased by about 13% in 'Chandler,' 18% in 'Oso Grande,' and 25% in 'Sweet Charlie' cultivars, with 'Sweet Charlie' being the only cultivar that showed an increase in total anthocyanins comparable to that observed in field-ripened strawberry (Nunes et al. 2006). Fully ripe strawberries stored in fluctuating temperatures had a higher anthocyanin content than fruit held at constant temperature (Nunes et al. 2003b). Color of strawberries is, therefore, dependent upon anthocyanin content, which is affected by cultivar, storage time, and storage temperature (Spayd and Morris 1981c).

L* value of the fruits tended to decrease during storage, particularly in fruits stored at 20°C or in riper fruit (Nunes and Emond 2002; Nunes et al. 2006). In fact, fruits were more dark red (lower L* value) after storage than at the time of harvest. L* value of strawberries stored at lower temperatures decreased after 2 days but remained stable thereafter. L* value of strawberries decreased during storage, and a progressive increase in surface darkening (decrease in L* value) was observed during storage (Nunes and Emond 1999; Péneau et al. 2007; Paraskevopoulou-Paroussi et al. 1995; Sacks and Shaw 1993). However, Collins and Perkins-Veazie (1993) reported no significant difference in L* values of 'Cardinal' strawberries stored under different simulated retail storage temperature conditions. Hue of 'Seascape' strawberries decreased during storage, regardless of the storage temperature, and at the end of storage the fruit was more purplish-red than red when compared to fresh harvested fruits (Nunes and Emond 2002). The hue angle of strawberries decreased significantly (i.e., red color development) during storage for 8 days at 1°C, regardless of the initial color stage of the fruit (Nunes et al. 2006). Chroma of 'Seascape' strawberries decreased during storage, but the decrease was more evident in fruit stored at temperatures above 5°C. During storage, the color of the fruits became less vivid (lower chroma values) than at the time of harvest (Nunes and Emond 2002). Collins and Perkins-Veazie (1993) also observed a decrease in hue and chroma of 'Cardinal' strawberries during storage, regardless of the temperature. Decreased chroma values during storage corresponded to the development of a red-brownish color in fully ripe strawberries stored for 8 days at 1°C (Nunes et al. 2006).

Firmness of 'Seascape' strawberries decreased during storage, regardless of the storage temperature (Nunes and Emond 2002). Fruit firmness in stored fruit was considered unacceptable after 2 days at 20°C. After 3 days, strawberries stored at 15°C were more soft than firm, whereas fruit stored at 0 and 5°C for 7 days maintained an acceptable firmness (Nunes and Emond 2002). Luoto (1984) reported that strawberries tended to lose firmness when transferred from low-temperature storage to higher temperatures. Nunes and Emond (1999) observed that strawberries stored for 1 day at 1°C were firmer than those stored for the same period at 5.5°C, but when transferred to 10°C for 1 day, fruit firmness decreased, regardless of previous temperature regimen. Paraskevopoulou-Paroussi et al. (1995) reported that firmness of strawberries stored at 20°C decreased significantly after 6 days. Smith and Heinze (1958) harvested strawberries at different stages of color development from quarter-colored to fully colored, and observed that firmness decreased after storage at 0°C, regardless of the color stage, but partially colored fruits were firmer and bruised less than full-red berries. As storage temperature increased from 2 to 43.5°C, flesh firmness and skin toughness decreased (Ourecky and Bourne 1968). Strawberries stored for 3 days at 1°C were firmer than those stored at 5°C, and after 11 and 15 days fruits stored at 1°C were much firmer than those stored at 5°C. Therefore, the greater softness of the fruits may be attributed to the exposure to the higher temperatures during storage (Collins and Perkins-Veazie 1993). In addition, when strawberries were exposed to fluctuating temperatures during handling, they softened faster than fruit held at constant temperatures (Nunes and Emond 1999; Nunes et al. 2003b).

Storage temperature also has a significant effect on the development of decay. For example, at 18°C and 95% relative humidity, strawberry fruit rot developed rapidly, with more than 35% of the fruit showing decay after 2 days in storage (Takeda et al. 1990). Decay increased rapidly in strawberries stored at 10°C, particularly after 7 days of storage, whereas fruit stored at 5°C had slight fungal decay after 13 days of storage. Furthermore, fungal decay was the major cause of strawberry fruit deterioration after 3 days at 20°C, and after 4 days at 10°C (Shin et al. 2007). Conversely, storage at 0°C was very effective in suppressing decay in strawberries (Ayala-Zavala et al. 2004). Without refrigeration, conidia of *Botrytis cinerea* invaded strawberry fruits rapidly, mostly when the fruit was wounded, whereas spore germination and growth were very slow at temperatures less than 5°C (Sommer et al. 1973). At 2°C the development of gray mold lesions was very small, whereas at 0°C lesion development was not detectable (Sommer et al. 1973). The maturity stage of strawberries can influence the development of decay, since when strawberries were harvested with white tips, decay development was lower than in fruits harvested at the full-red stage (Pritts et al. 1987).

Strawberry fruit stored at 5 or 10°C generally produces higher levels of aroma volatiles compared to fruit stored at 0°C (Ayala-Zavala et al. 2004). However, loss of aroma was faster in 'Seascape' strawberries stored at temperatures higher than 0°C (Nunes and Emond 2002). For example, aroma of 'Seascape' strawberries stored at 15 and 20°C was considered unacceptable due to off-flavors after approximately 1–2 days, whereas fruits stored at 0, 5, and 10°C maintained an acceptable aroma after approximately 6, 5, and 4 days, respectively. Loss of taste followed the same pattern as loss of aroma for 'Seascape' strawberries stored at 15 and 20°C. In fruits stored at 0, 5, and 10°C, the taste was no longer acceptable after approximately 6, 5, and 2 days, respectively, due to the development of off-flavors and musty taste (Nunes and Emond 2002). Freshness of strawberries stored at 0°C decreased during storage, resulting in fruit with fermented and sour odor and flavor after 9 days (Péneau et al. 2007).

Robinson et al. (1975) reported that a 6% weight loss was the maximum for strawberry marketability. After approximately 2 days at 20°C, 'Seascape' strawberries had lost 6% of their initial weight, whereas fruit stored at 0, 5, 10, and 15°C had an average loss of 3% (Nunes and Emond 2002). Shriveling of strawberries stored at 20°C was moderate after approximately 2 days, and corresponded exactly to the 6% weight loss. Fruits stored at 10 and 15°C had moderate shriveling after 4 and 6 days, respectively, and corresponded to weight losses of approximately 2–3%. One of the reasons for reduced shriveling in strawberries inside the package could be the high humidity inside the package, which was maintained at around 95–100% throughout the storage period (Nunes and Emond 2002). Nunes et al. (1998) observed that when strawberry fruit was stored for 8 days at 1 or 10°C or 4 days at 20 °C, weight loss increased with temperature. In another study, Nunes and Emond (1999) reported that fruit stored at 5.5°C lost only 0.3% of its initial weight after 6 days in storage, and suggested that loss of weight during storage may be minimized by holding the strawberries in vented plastic containers. Weight loss of strawberries stored in fluctuating temperatures was significantly higher than that of fruit stored in constant temperatures (Nunes and Emond 1999; Nunes et al. 2003b).

Water loss during storage has a major influence on vitamin stability. Maintaining a low temperature and high humidity during postharvest storage may delay degradation of ascorbic acid (Barth et al. 1990; Nunes et al. 1998). In strawberry fruit stored for 8 days at 1 or 10°C, or 4 days at 20°C, weight loss and ascorbic acid degradation increased with increasing the temperature. Postharvest life was extended and losses of ascorbic acid reduced by an average of 7.5-fold when strawberries were held at 1°C during the postharvest period (Nunes et al. 1998). When strawberries were handled under fluctuating temperatures, ascorbic acid losses were slightly higher than in fruit held at constant temperature (Nunes et al. 2003b). Kenny (1979) observed that ascorbic acid decreased very little in strawberries stored for up to 4 days at 2°C plus 1 day at 20°C, and concluded that ascorbic acid in the fruit was well preserved during storage at low temperatures. However, strawberries can lose their vitamin C content rapidly if bruising occurs. When cell walls are damaged, the enzyme ascorbate oxidase, normally present in the cells, is released and oxidizes the vitamin (Klein 1987; Nobile and Woodhill 1981). Occasionally increases in the ascorbic acid content of strawberries may occur after harvest, perhaps from increased ascorbic acid synthesis during storage (Cordenunsi et al. 2005; Nunes et al. 1998, 2006; Olsson et al. 2004). The ascorbic acid content of ‘Chandler’ strawberries harvested either half-colored, three-quarters colored, or full-red increased by 21.5, 18.5, and 17%, respectively, after 8 days at 1°C (Nunes et al. 2006). A 10% increase in the ascorbic acid of three-quarters red ‘Oso Grande’ strawberries after storage at 16°C was also observed (Cordenunsi et al. 2005).

Several other changes occur in strawberry chemical composition throughout the postharvest period. A slight decrease in acidity and soluble solids content of strawberries was seen with increased storage time at 5, 10, 20, or 30°C, whereas strawberry pH did not change (Ayala-Zavala et al. 2004; Kalt et al. 1993). During storage at 1°C, fruit pH did not change significantly after harvest, regardless of the maturity stage at harvest (Ayala-Zavala et al. 2004; Nunes et al. 2006). Changes in acidity are dependent upon fruit maturity and storage temperature (Kalt et al., 1993; Salunkhe et al., 1991; Spayd and Morris 1981a). Smith and Heinze (1958) observed a decrease in sugars and acids in full-red strawberries stored at 0°C, whereas Collins and Perkins-Veazie (1993) concluded that soluble solids content and total acidity of strawberries did not change significantly when fruit was stored for 8 days at 1 or 5°C. However, the acidity of strawberries harvested at different stages of development tends to increase during storage at 1°C, and fruit harvested three-quarters colored had almost the same acidity after storage as full-red colored strawberries at the time of harvest (Nunes et al. 2006).

Changes in the soluble solids content of strawberries during storage depends on temperature and initial ripeness. The soluble solids content of ‘Oso Grande’ increased by 10, 6.5, and 7% during storage at 1°C in fruit harvested at the color break, half-color, and three-quarters-colored stages, respectively, whereas in ‘Chandler’ strawberries harvested full-red colored, soluble solids content increased by 9% during storage (Nunes et al. 2006). Cordenunsi et al. (2005) reported an increase of up to 30% in the total soluble sugars of full-size, three-quarters red ‘Oso Grande’ strawberries during storage at 6°C for 6 days. Overall, after 8 days at 1°C, the soluble solids content of half-colored and three-quarters-colored strawberries was only 10 and 5% lower, respectively, than that of full-red colored fruit at the time of harvest (Nunes et al. 2006). However, after 11 days at 10°C, soluble solids content of strawberries showed a higher decrease when compared to soluble solids content of fruit stored at lower temperatures (Ayala-Zavala et al. 2004). ‘Blomidon’ strawberries harvested at early stages of color development (one-half to three-quarters colored) and stored for 8 days at 5, 10, 20, or 30°C did not show sufficient changes in sugar and acid content to be suitable for fresh consumption (Kalt et al. 1993).

Although strawberries harvested at different stages of color development continued their development during storage at 1°C, only the more advanced three-quarters and full-ripe fruit exhibit changes consistent with ripening. Overall, strawberries harvested at the three-quarters-colored stage continued to change in acidity, soluble solids, ascorbic acid, total anthocyanins, and total soluble phenolic contents during storage for 8 days at 1°C, with final values similar to those of full-red colored strawberries (Nunes et al. 2006).

Time and Temperature Effects on the Visual Quality of ‘Seascape’ Strawberries

‘Seascape’ strawberries shown in Figures 3.26–3.30 were harvested at the three-quarters-colored stage from a commercial operation in Saint-Nicolas, Quebec, Canada, during the fall season (i.e., October). Promptly after harvest, fresh strawberries were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Strawberries can be stored for a longer period without losing their red color and firmness (Nunes et al. 2006). ‘Seascape’ strawberries harvested at the three-quarters-colored stage continued to develop red color after harvest, and color develops faster when fruit is stored at temperatures higher than 0°C. The redness of strawberries stored at 0°C changes slightly during storage, with only a slight reduction of the whitish surface area on the strawberry shoulders after 8 days. The fruit calyx becomes less turgid as storage progresses, but the fruit maintains an acceptable appearance during 7–8 days of storage (Figure 3.26).

Strawberries stored at 5°C have an acceptable visual quality for 6 days. Thereafter, fruit quality starts to deteriorate. After 4 days, the color of the fruit darkens slightly, and after 8 days the whitish surface area on the strawberry shoulders diminishes and becomes more reddish. After 3 days, minor defects such as spots of water-soaked tissue are noticeable, which increase after 8 days (Figure 3.27).

When stored at 10°C, strawberries develop a full-red color within 8 days of storage but appear overripe. After 6 days, decay develops on the fruit surface, and the lower part of the fruit is covered with gray mold after 8 days. Some yellowing of the calyx also develops, and the calyx of the fruit appears dry and more yellow than green after 8 days (Figure 3.28).

With storage at 15°C, strawberry color changes quickly, with red color developing in 4 days on white areas. Decay is evident at the base of the fruit, increasing to 75% of the fruit after 5 days, and 100% after 8 days (Figure 3.29).

Changes in the color of ‘Seascape’ strawberries stored at 20°C are extremely rapid, with complete red color after only 2 days. After 2 days, a very slight brownish-red sunken area appears at the lower right side of the fruit, and after 3 days decay has already spread to almost half of the fruit surface. By day 4 the fruit is completely covered with gray mold. After 8 days, the fruit and calyx are completely covered with gray mold (Figure 3.30).

Overall, changes in color (from white-pink to full-red) and development of visible decay are the two major changes in strawberry visual quality during storage. Changes occur more rapidly as storage time and temperature increase. Three-quarters-colored ‘Seascape’ strawberries stored at 0°C maintain a better visual quality for longer periods (8 days) when compared to fruit stored at higher temperatures. Strawberries stored at 5, 10, 15, and 20°C maintain acceptable visual quality for 6, 5, 1, and 1 day, respectively.

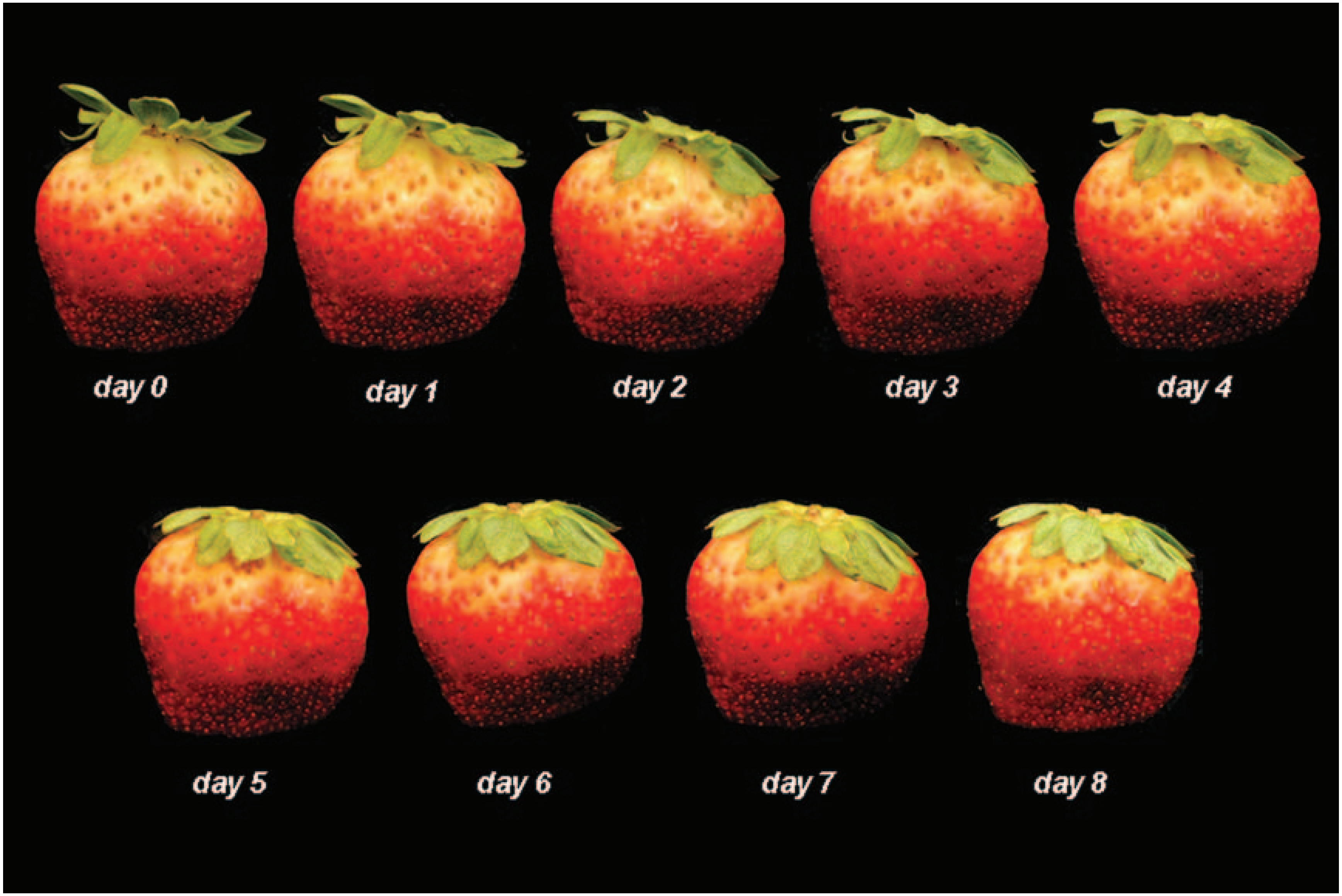
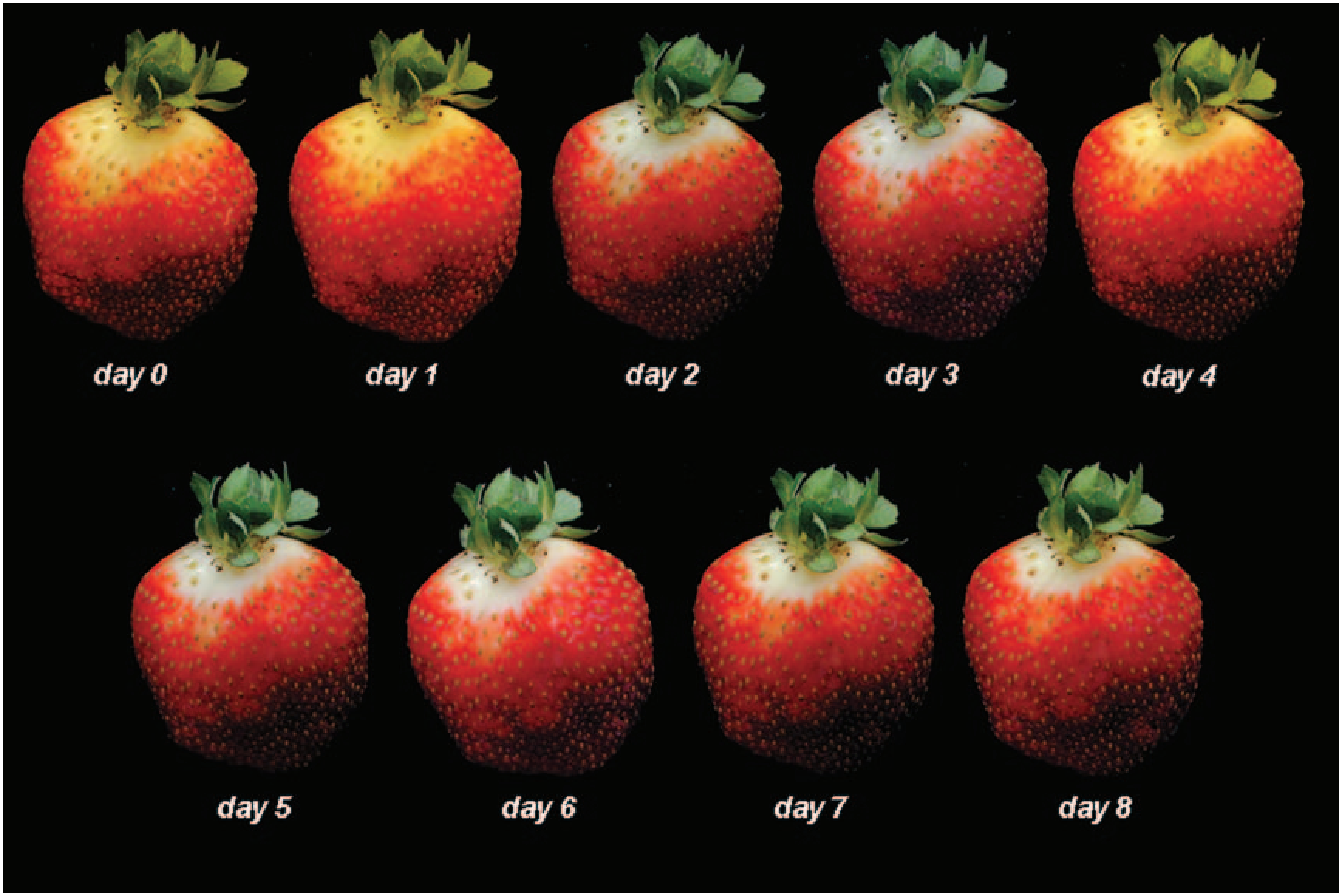

day 0
day 1
day 2
day 3
day 4
day 5
day 6
day 7
day 8

Figure 3.26. Appearance of 'Seascape' strawberry stored for 8 days at 0°C. Fruit maintains an acceptable appearance during 7 or 8 days of storage. The calyx of the fruit becomes less turgid and less green after 8 days.


day 0
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day 3
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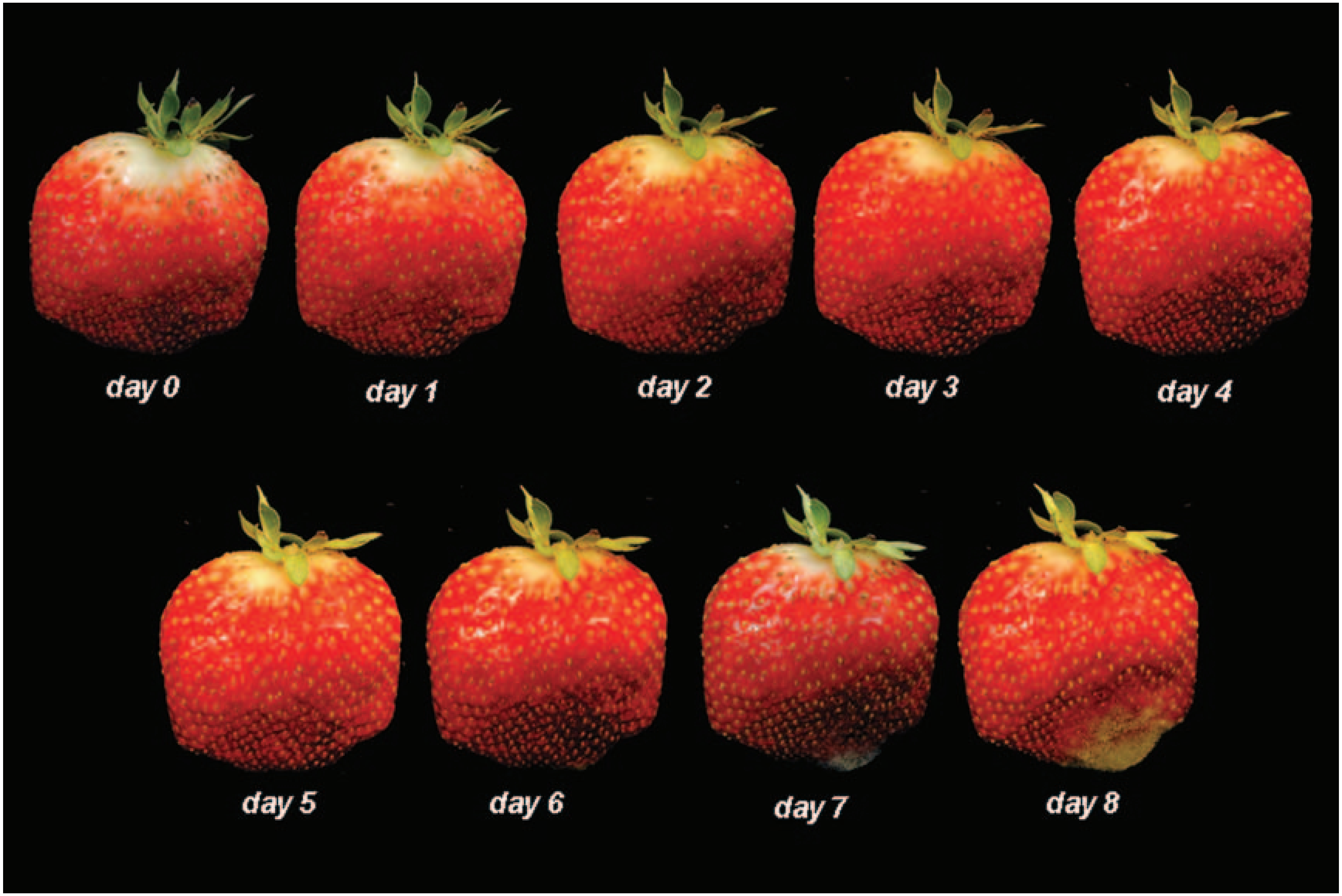
day 5
day 6
day 7
day 8

Figure 3.27. Appearance of 'Seascape' strawberry stored for 8 days at 5°C. Fruit maintained an acceptable appearance during 6 days. After 4 days the color of the fruit darkened and some minor defects such as spots of water-soaked tissue are visible.


day 0
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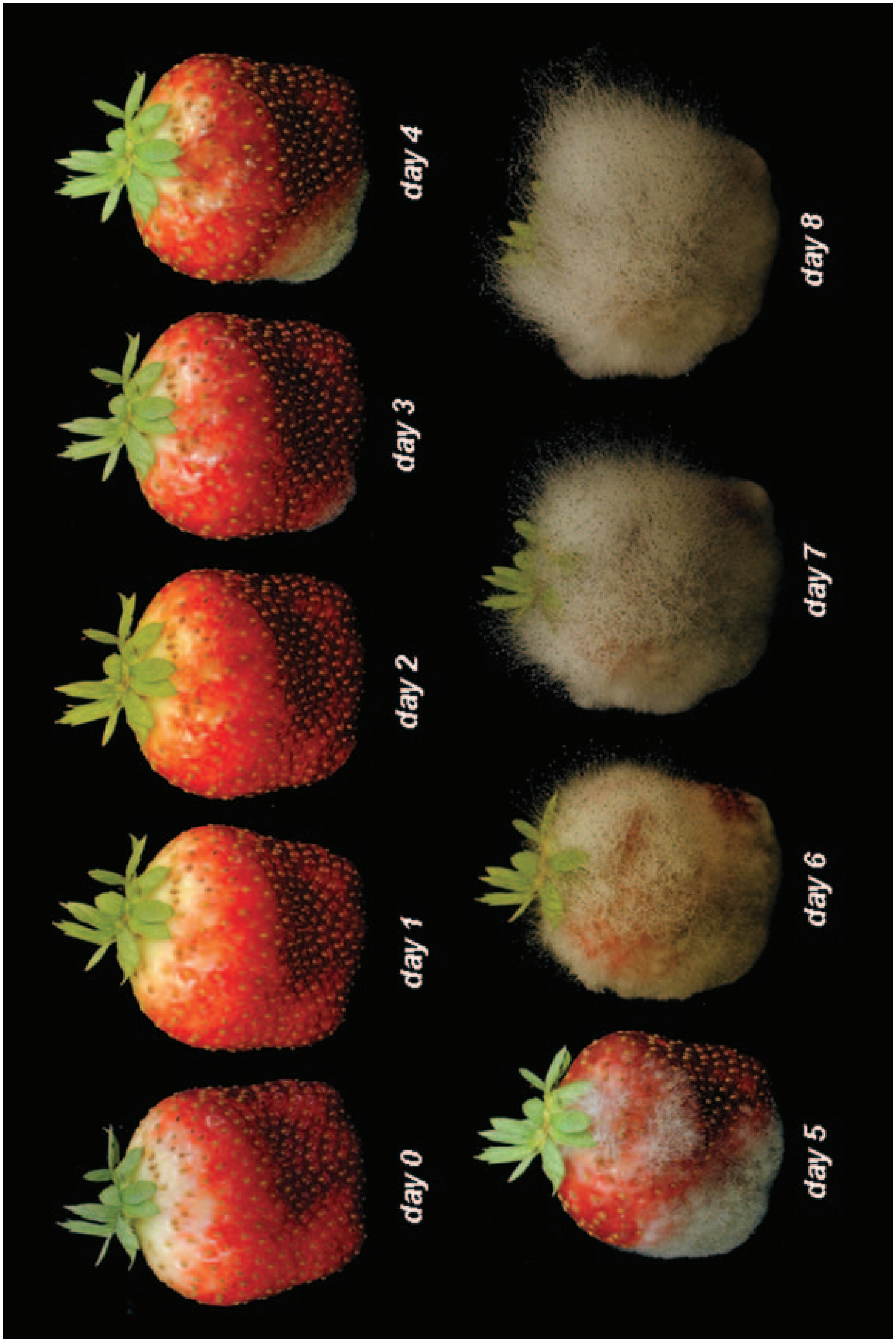
day 5
day 6
day 7
day 8

Figure 3.28. Appearance of 'Seascape' strawberry stored for 8 days at 10°C. Fruit maintains an acceptable appearance during 5 days. After 4 days the color of the fruit darkens and after 8 days the fruit develops severe decay.


day 0
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day 3
day 4
day 5
day 6
day 7
day 8

Figure 3.29. Appearance of 'Seascape' strawberry stored for 8 days at 15°C. Fruit maintains an acceptable appearance during 2 days. After 3 days of storage, the color of the fruit darkens while mold develops. After 8 days the fruit is completely covered with gray mold.

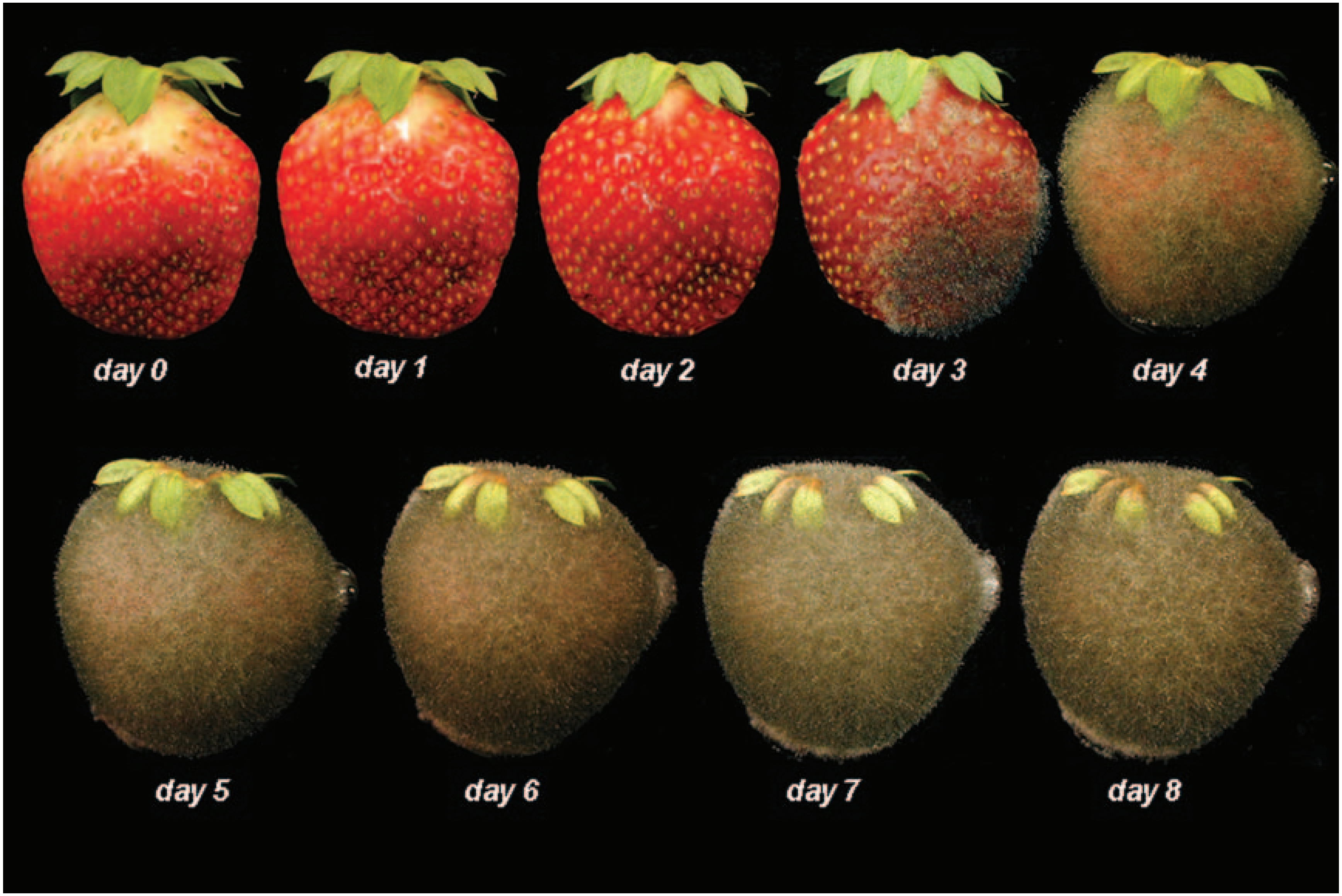
day 0
day 1
day 2
day 3
day 4
day 5
day 6
day 7
day 8

Figure 3.30. Appearance of 'Seascape' strawberry stored for 8 days at 20°C. Fruit maintains an acceptable appearance during 2 days. After 2 days the fruit is completely red, and after 3 days mold growth is evident. After 8 days the fruit is completely covered with gray mold.

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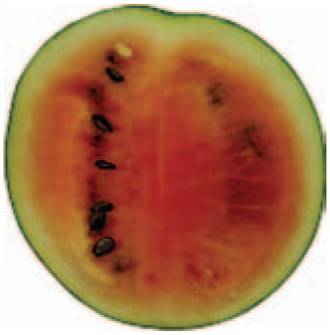

CHAPTER 4

CUCURBITACEAE

Cantaloupe
Watermelon
Yellow Squash
Bibliography

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CANTALOUPE

Scientific Name: *Cucumis melo* L. var. *reticulatus* Naud.
Family: Cucurbitaceae

Quality Characteristics

Cantaloupe, also known as muskmelon or netted melon, is a warm-season crop. In general, cantaloupe melons are ready to harvest when the firm-ripe stage is attained, or when a clear abscission from the vine occurs with light pressure, that is, at the three-fourths to full slip (Shellie and Lester 2004; Suslow et al. 2006). One-quarter slip cantaloupe have a clear green, well-attached peduncle; half-slip fruit has a distinct abscission visible at the peduncle; three-fourths slip fruit is fruit approaching commercial harvest; and full-slip fruit separates easily from the vine with slight pressure (Beaulieu 2006). Abscission-zone development also corresponds to changes from green to yellow in cantaloupe rind background color (Shellie and Lester 2004). Another maturity or quality index is related to the aesthetic of net formation. Net formation during development of cantaloupe is an important indicator of fruit maturity and quality, and is also considered a preventive factor against mechanical injury during fruit development and postharvest handling. Netting of cantaloupe starts toward the end of the fruit-expansion phase, when a few rings of net tissue appear around the blossom scar, caused by natural cracks on the fruit epidermal layer. The number of concentric rings increases throughout development, and when cantaloupe reaches the mature phase the rings cover the entire fruit (Keren-Keiserman et al. 2004).

High-quality cantaloupe should be round and well shaped, have uniform tan-colored net, greenish-yellow rind background color, and bright orange flesh. The fruit should have a smooth, not wet or slippery stem-end, without stem attached; should be firm; and should have a firm internal cavity without free seeds or liquid accumulation. In addition to good external and internal appearance, cantaloupe should have at least 9–11% soluble solids content (Aubert and Bourger 2004; Shellie and Lester 2004; Suslow et al. 2006; Yamaguchi et al. 1977). European cantaloupe-type melons and some cultivars from California were reported to have much higher soluble solids content, ranging from 12.3 to 16.0% (Aubert and Bourger 2004; Aulenbach and Worthington 1974). Although soluble solids content of greater than 8% was not always associated with high fruit sweetness, flavor, or acceptability, in general, high soluble solids content resulted in high sweetness ratings. Therefore, muskmelons with soluble solids content above 12% received high sweetness scores (Aulenbach and Wortingthon 1974).

If harvested at the proper maturity stage, cantaloupe will continue to soften and will become more aromatic during storage. Cantaloupe harvested before full maturity may produce aroma volatiles and may never attain acceptable sugar content (Shellie and Lester 2004; Suslow et al. 2006). Although flavor volatile concentration and composition may vary depending on the cultivar, in general, as cantaloupe ripens the concentration of volatiles responsible for the characteristic flavor of ripe fruit increases from the immature to the full mature stage, and then decreases when fruit reaches the overripe stage (Aubert and Bourger 2004; Beaulieu 2006; Beaulieu and Grimm 2001; Horvat and Senter 1987; Kourkoutas et al. 2006; Senesi et al. 2005). Therefore, green-ripe cantaloupe lacks flavor, and as the fruit reaches the full ripe stage volatile compounds that are responsible for the fruity characteristic flavor of the fruit are produced at a rapid rate. With advanced ripening, cantaloupe develops an unpleasant flavor associated with the overproduction of certain volatiles, especially alcohols (Beaulieu 2006; Senesi et al. 2005; Yabumoto et al. 1978).

Cantaloupe textural integrity and firmness decrease during ripening, owing to changes in the composition and solubility of cell wall polysaccharides, including pectin, hemicelluloses, and cellulose (Guis et al. 1997; Simandjuntak et al. 1996). Cellulose provides rigidity and resistance to tearing, whereas pectin and hemicellulose contribute to tissue elasticity (Simandjuntak et al. 1996). Pectin-fraction yield increased by 10% from the unripe to ripe stages, and by 14% from the ripe to overripe stages, suggesting that pectin solubilization occurred as maturity increased. Conversely, hemicellulose fraction decreased as maturity of cantaloupe increased. Pectin and hemicellulose were solubilized at the same time that softening of cantaloupe occurred (Simandjuntak et al. 1996).

Cantaloupe background rind color changes during ripening; the color darkens and changes from a pale green to a yellowish-green, and then to a light yellow. Visual changes in color of cantaloupe during ripening are translated by a decrease in brightness (L* value). In general, an increase in hue, indicating a shift from green to light yellow and then to darker yellow, occurs during ripening (Nuñez-Palenius et al. 2007; Senesi et al. 2005; Simandjuntak et al. 1996).

Visual changes in the color of the rind and flesh result from the degradation and/or synthesis of pigments. At the onset of ripening, chlorophyll is rapidly lost, whereas carotenoid content increases (Guis et al. 1997). Increase in the intensity of flesh orange color during ripening results from chlorophyll degradation and carotenoid accumulation, of which β-carotene is the major component (Reid et al. 1970).

Soluble solids content, pH, total sugars, and protein and carbohydrate contents increase from the unripe to the ripe stage and then decline at the overripe stage. Acidity initially increases throughout early fruit development and then decreases sharply during ripening. Sucrose content increases continuously throughout fruit development, whereas glucose and fructose contents increase from the unripe to the ripe stage, and then decrease from the ripe to overripe stage (Bianco and Pratt 1977; Dull et al. 1989; Guis et al. 1997; McCollum et al. 1988; Nuñez-Palenius et al. 2007; Senesi et al. 2005; Simandjuntak et al. 1996; Villanueva et al. 2004). The rapid increase in total sugars during ripening was attributed to increases in sucrose (Beaulieu et al. 2003; Guis et al. 1977; Villanueva et al. 2004), and almost half of the final concentration of sugar in cantaloupe was achieved in the last week before or at the time of abscission (Bianco and Pratt 1977; McCollum et al. 1988). Therefore, harvesting of immature cantaloupe fruit will have a negative effect on flavor, composition, and eating quality.

The overall quality of cantaloupe is based on attributes including appearance, eating quality, and nutritional value. Final acceptance by consumers depends on the combination of aroma, taste, and texture (Senesi et al. 2005). Sweetness was considered the most important attribute in the determination of cantaloupe eating quality, followed by aroma and flesh color, and by texture (Yamaguchi et al. 1977). Finally, melons should be harvested when light yellow with some green areas in order to obtain a desirable aroma and taste and to maintain overall quality and prolonged postharvest life (Fallik et al. 2001).

Cantaloupe is low in fat and sodium, has no cholesterol, and is an excellent source of potassium, vitamin C, and provitamin A, or β-carotene (Lester 1977). Cantaloupe contains on average 90% water, 0.8% protein, 8% carbohydrate, 1% fiber, and 234–267 mg of potassium, 20–62 mg of vitamin C, 1,558–2,055 µg of β-carotene, and 3,382 IU of vitamin A per 100 g fruit fresh weight, as well as small amounts of phenolics (6–12 mg per 100 g fruit fresh weight)(Bushway et al. 1986, 1989; Eitenmiller et al. 1985; Gil et al. 2006; Holden et al. 1999; USDA 2006; Vanderslice et al. 1990; Vinson et al. 2001; Wills et al. 1984).

Optimum Postharvest Handling Conditions

To delay ripening and retain sugar content, cantaloupe should be pre-cooled promptly after harvest to a fruit center temperature of 10–15°C, preferably using hydro-cooling (Shellie and Lester 2004). Cantaloupe fruit is sensitive to low temperatures and, therefore, should be stored at temperatures between 2 and 7°C. Holding cantaloupe for 7 days at temperatures below 2°C may result in chilling injury (CI). However, when stored at 2°C, the expected postharvest life of cantaloupe is about 10–21 days. A relative humidity of between 90 and 95% is recommended to avoid excessive moisture loss (Shellie and Lester 2004; Suslow et al. 2006).

Temperature Effects on Quality

After harvest, the visual, textural, sensorial, and compositional quality attributes of cantaloupe change owing to the natural process of fruit ripening and aging. However, the rate of change in fruit quality is greatly dependent on temperature and humidity. Cantaloupe is relatively sensitive to low storage temperatures, and when stored for extended periods at temperatures below 2°C, the fruit may develop CI. Symptoms of CI are characterized by pitting or sunken areas of the rind, failure to ripen, off-flavors, and increased surface decay (Shellie and Lester 2004; Suslow et al. 2006). In general, symptoms of CI are more acute when cantaloupe is transferred to higher temperatures after being exposed to chilling temperatures. Sensitivity to CI decreases as cantaloupe maturity and ripeness stage increase. For example, full-slip cantaloupe may be stored for 5–14 days at 0–2°C, whereas less mature melons may be damaged by holding at temperatures lower than 2°C. Cantaloupe melons stored at 2°C for 7, 14, or 21 days showed depressed surface browning and pitting when transferred to 22°C for 4 additional days. Upon removal from chilling temperature, some fruit exhibited severe CI symptoms, even when stored for only 7 days at 2°C; the disorders were aggravated in fruit stored for 14 days at 2°C, and after 21 days none of the fruit was considered acceptable for sale (Flores et al. 2004).

Depending on storage time and temperature, color of cantaloupe changes from a light yellowish-green to a deeper yellow. Brightness (L* value) of ripe cantaloupe stored for 7 days at 2°C increased or decreased, whereas hue angle increased and chroma decreased (Senesi et al. 2005). During storage for 9 days at 5°C, no significant changes were observed in the b* value of cantaloupe (Gil et al. 2006). In 'Galia' melons stored at 5°C, a* value increased until 7 days of storage and remained constant thereafter, whereas in melons stored at 8°C an increase in a* value was observed only after 14 days of storage (Bigalke and Huyskens-Keil 2000). Color of 'Galia' muskmelons changed during storage from a light yellow with some green areas at the time of harvest, to a dark orangish-yellow after 14 days at 5 to 6°C plus 3 days at 17°C (Fallik et al. 2005).

Firmness of cantaloupe decreases during storage, regardless of the storage temperature (Gil et al. 2006; Halloran et al. 1999a, 1999b; Lester and Bruton 1986; Lester and Grusak 2004; Senesi et al. 2005). After 7 days at 2°C, firmness of ripe cantaloupe decreased by about 6 or 15%, depending on the cultivar (Senesi et al. 2005). Firmness of muskmelons stored at 4°C decreased during storage and was greatly affected by the humidity levels. Muskmelons stored unwrapped at 85–95% relative humidity were less firm after

40 days of storage compared to fruit that was wrapped in a plastic film, and thus maintained in a water-saturated environment (Lester and Bruton 1986). Firmness of cantaloupe decreased during storage at 5°C, and after 9 days initial fruit firmness was reduced by 36% (Gil et al. 2006). Likewise, whole fruit firmness and mesocarp firmness of cantaloupe significantly decreased during storage for 1 or 2 weeks at 10°C (Lester and Grusak 2004).

Weight loss of muskmelons increases during storage, regardless of the temperature. However, weight loss is generally higher when melons are stored at high temperatures and low humidity levels. Weight loss of 'Galia' melons reached 5.7% after storage for 14 days at 5–6°C plus 3 days at 17°C (Fallik et al. 2005), whereas after 40 days at 4°C initial weight of muskmelons declined by 1 and 11.2% in film-wrapped or unwrapped fruit, respectively (Lester and Bruton 1986). Nonwrapped muskmelons with an average weight loss of 5% after 20 days at 4°C were soft and with sunken surface areas, and 60% of the fruit was considered unacceptable for sale (Lester and Bruton 1986). Appearance of melons with less than 4% weight loss was considered acceptable, and there were no signs of physical shriveling (Cohen and Hicks 1986). Keeping netted muskmelons in a high-humidity environment may retard the promotion of enzyme-substrate interactions, due to the maintenance of full cellular hydration and reduction in cell disorganization, and thereby extend fruit postharvest life (Lester and Bruton 1986). Depending on the cultivar, weight loss of cantaloupe stored at 2°C attained a maximum of approximately 8–9% after 21 days of storage (Flores et al. 2004). After 35 days at 2°C and 85–90% relative humidity, weight loss of unwrapped cantaloupe melons reached 8.34%, whereas weight loss of fruit packed in a plastic film was only 0.55%. However, infection rate was much higher, and affected 100% of the wrapped fruit compared to 66.67% infection in unwrapped fruit (Halloran et al. 1999a).

Cantaloupe composition is also affected by the storage temperature. For example, ripe cantaloupe stored for 7 days at 2°C showed a decrease in acidity, soluble solids, and fructose and glucose contents, and an increase in pH, total sugars, and sucrose content (Senesi et al. 2005). Likewise, acidity and soluble solids content of cantaloupe stored at 2°C significantly decreased after 35 days of storage (Halloran et al. 1999b). However, no significant changes were observed in the soluble solids content, acidity, and pH of cantaloupe stored for 6 days at 5°C (Gil et al. 2006). Likewise, soluble solids content of 'Galia' muskmelons stored at 5°C remained almost constant during 14 days of storage; yet in fruit stored at 8°C soluble solids content declined after 7 and 14 days of storage (Bigalke and Huyskens-Keil 2000). Soluble solids content of orange-fleshed cantaloupe also decreased during storage for 1 or 2 weeks at 10°C (Lester and Grusak 2004), whereas 'Galia' muskmelons showed a decrease in soluble solids content from 12.9 to 10.2% after 14 days at 5–6°C plus 3 days at 17°C (Fallik et al. 2005). Muskmelons stored at 4°C showed an increase in fructose and glucose contents after 10 days, whereas sucrose content decreased significantly. However, after 20 and 40 days at 4°C there was a progressive decrease in all sugars (Lester and Bruton 1986). Glucose levels in melons stored for 10 days at 5, 10, 15, and 20°C decreased with storage duration and temperature, but the greatest rates of decrease were observed in melons stored at 20°C (Cohen and Hicks 1986).

Melons lacked flavor and sweetness when soluble solids content was very low, whereas melons with high soluble solids content were considered flavorful (Cohen and Hicks 1986). Lester and Bruton (1986) suggested that if the percentage fresh weight loss was greater than the percentage of sugar loss, netted muskmelon might taste sweeter after storage, but if the percentage of dry weight loss was less than the percentage of sugar loss, muskmelon would taste less sweet. Muskmelons stored for 20 days at 4°C had a 13% loss in total sugars and a 5.7% and 0.3% loss in fresh and dry weight, respectively, and thus tasted less sweet than at harvest (Lester and Bruton 1986). Furthermore, after storage of cantaloupe for 7 days at 2°C there was a general decrease in the aroma profile of the fruit, particularly for esters and alcohols (Senesi et al 2005). 'Galia' melons stored for 14 days at 5–6°C plus 3 days at 17°C had a good taste, but off-flavors developed after storage (Fallik et al. 2005).

Ascorbic acid content of cantaloupe decreased from an initial value of 62 mg per 100 g fruit fresh weight to 44.6 mg per 100 g fruit fresh weight after 12 days at 20°C, which represented a decrease of than more than 30%. After 12 days at 20°C, when cantaloupe was considered unacceptable for consumption, initial ascorbic acid content was reduced by more than 50% (Wills et al. 1984). Conversely, vitamin C, β-carotene, and phenolic content were well preserved in cantaloupe stored for 9 days at 5°C (Gil et al. 2006).

Time and Temperature Effects on the Visual Quality of 'Athena' Cantaloupe

'Athena' cantaloupe shown in Figures 4.1–4.9 was harvested at the mature full-slip, firm-ripe stage from a commercial operation in Dover, Florida, during the spring season (i.e., May). Promptly after harvest, fresh cantaloupes were stored at five different temperatures (0.5 ± 0.3°C, 5.0 ± 0.2°C, 9.4 ± 0.4°C, 14.40 ± 0.4°C and 20.0 ± 0.2°C) with 95–98% relative humidity.

Visual quality attributes of 'Athena' cantaloupe change during storage, but the type, severity, and rate of changes depend on storage time and temperature. Major visual changes during storage of cantaloupe at temperatures below 5°C are mainly related to CI. In cantaloupe stored at temperatures above 5°C, changes in the color from a greenish-yellow to yellow, brown discoloration, and decay are the major visual changes observed during storage.

'Athena' cantaloupe stored at 0°C maintains acceptable visual quality during 13 days. After 13 days, the melon develops areas of brownish and scald-like discoloration, which increase after 28 days (Figure 4.1). However, the area of the melon that was in direct contact with the soil deteriorates much faster, and after 15 days the rind develops a shriveled, scald-like, sunken, and greenish-yellow appearance. The severity of the injury increases as storage progresses, and after 28 days most of that area is affected (Figure 4.2). When cantaloupe stored at 0°C is transferred to 20°C for 2 additional days, visual quality deteriorates even faster owing to aggravation of CI symptoms. External symptoms of CI develop after 3 days at 0°C plus 2 days at 20°C. The fruit develops brownish or grayish discolored sunken lesions on the rind, whereas pitting, scald, and uneven ripening are also noticeable. Although the type and severity of the CI symptoms vary from fruit to fruit, it is evident that all of the fruit transferred to 20°C at different time intervals is affected by CI (Figure 4.3). Internal symptoms of CI in cantaloupe stored at 0°C develop after 15–21 days upon transfer to 20°C for 2 days. Water-soaking of the flesh becomes apparent after 15 days, and decay develops at the stem-end of the fruit after 21 days (Figure 4.4).

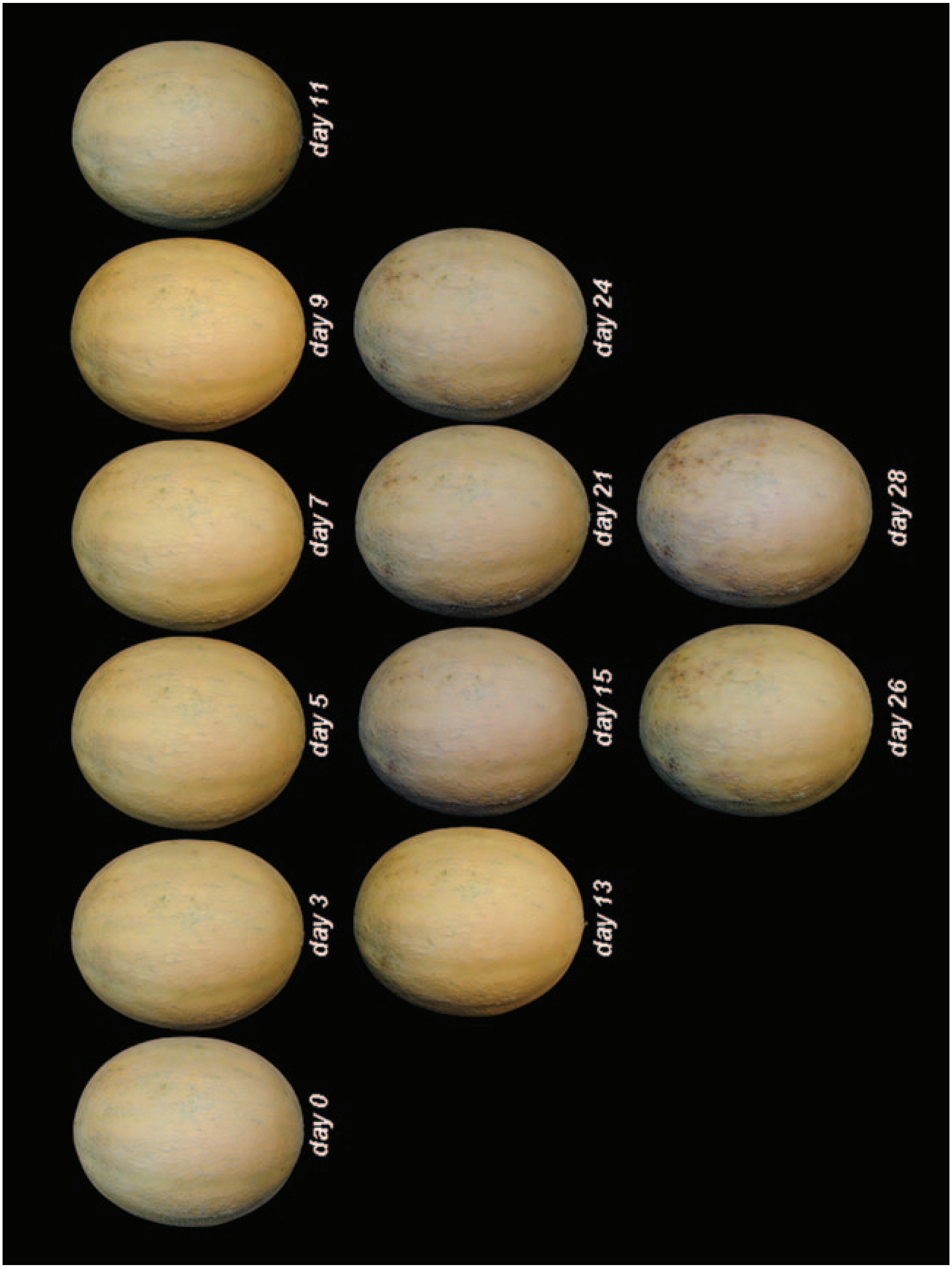
Visual quality of ‘Athena’ cantaloupe stored at 5°C starts to deteriorate after 13 days, owing to the development of small brownish areas on the rind, which increase in number and size as storage progresses. Incipient decay at the stem-end of the fruit is also noticeable after 26 days (Figure 4.5). Deterioration of the area of the melon that rests on the soil is much more severe that in other parts of the fruit, and after 21 days the rind develops a shriveled, sunken, and greenish-yellow appearance. After 28 days, the affected area of the fruit is extremely shriveled, discolored, and decayed (Figure 4.6).

During storage of cantaloupe at 10°C, rind color changes from a greenish-yellow to a light yellow. After 9 days, the fruit visual quality is very good, no defects are noticeable, and the color is light yellow with a subtle orange shade. Appearance of the fruit remains acceptable during 13 days, but thereafter small brownish areas develop on the rind, which increase slightly in number and size as storage progresses. Decay starts to develop at the stem-end of the fruit after 15 days, and after 19 days the area around the stem-end is severely decayed (Figure 4.7).

Changes in the color of ‘Athena’ cantaloupe are more rapid at 15°C than at 10°C. Within 3 days of storage at 15°C the color of the rind changes from yellowish-green to yellow, yet the fruit develops some brownish areas on the rind that result in severe decay after 15 days. Decay also develops faster and more severely in fruit stored at 15 than at 10°C, and after 11 days the area of the melon that rests on the soil deteriorates and appears severely sunken and decayed after 15 days (Figure 4.8).

Decay develops extremely quickly in cantaloupe stored at 20°C, spreading from the external to the internal tissues of the fruit, mainly through the stem-end scar. After 5 days, decay develops at the stem-end, and after 7 days the top portion of the fruit around the stem-end area collapses owing to severe decay. The internal tissue of the fruit around the stem-end area appears somewhat water-soaked and mushy (Figure 4.9).

Overall, ‘Athena’ cantaloupe stored at 5 or 10°C maintains acceptable visual quality for longer periods (13 days) compared to melons stored at 0, 15, or 20°C. Postharvest life of cantaloupe stored at 0°C is reduced to 3 days because of CI, whereas fruit stored at 15 and 20°C maintain acceptable visual quality for only 5 and 3 days, respectively. Afterward, quality deteriorates rapidly owing to the development of decay. Postharvest life of ‘Athena’ cantaloupe stored at 0°C is as long as that of fruit stored at 20°C.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day 28

Figure 4.1. Appearance of 'Athena' cantaloupe stored for 28 days at 0°C. Cantaloupe maintains acceptable visual quality during 13 days. After 13 days, the melon develops spots of brownish and scald-like discoloration, which increase with prolonged storage.

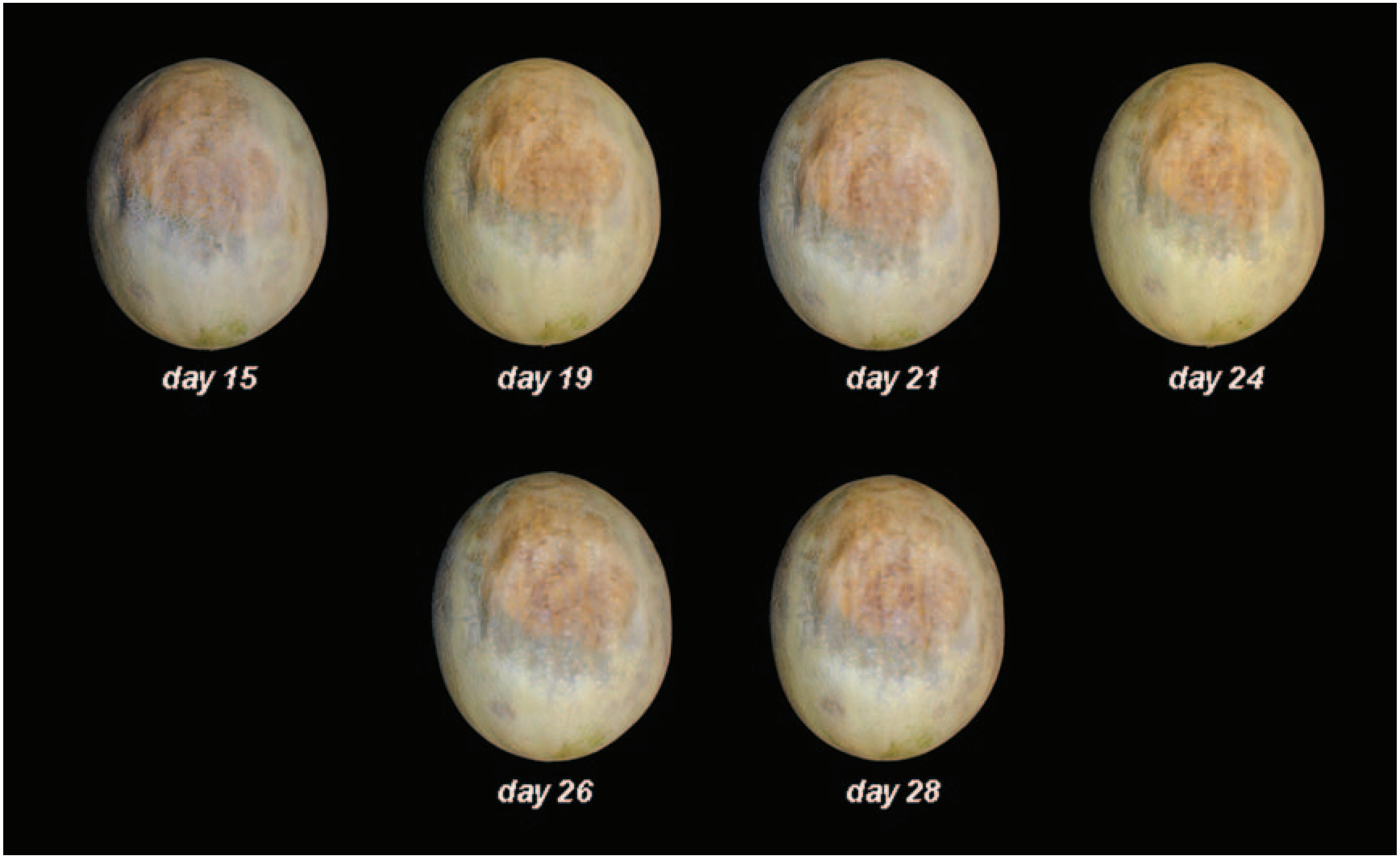

Figure 4.2. Appearance of 'Athena' cantaloupe stored for 28 days at 0°C (view of the area that touched the ground). After 15 days the area of the melon that touched the ground deteriorates, and the rind develops a shriveled, scald-like, sunken, and greenish-yellow appearance.

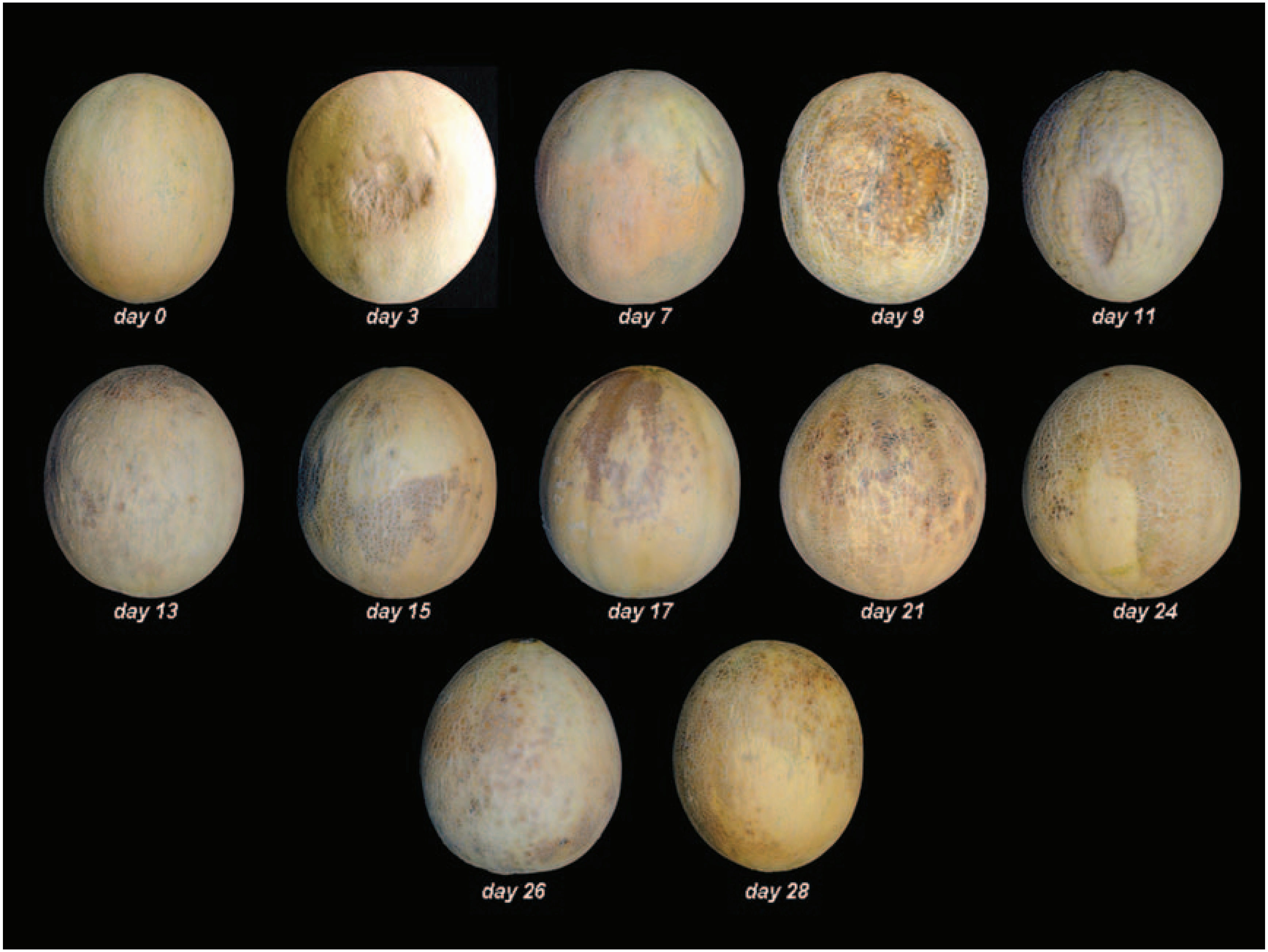
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Figure 4.3. External symptoms of CI in 'Athena' cantaloupe stored at 0°C after transfer to 20°C for 2 days. Cantaloupe stored for 3 days at 0°C and then transferred to 20°C for 2 additional days develops brownish or grayish sunken lesions on the rind, while pitting, scald, and uneven ripening are also noticeable.

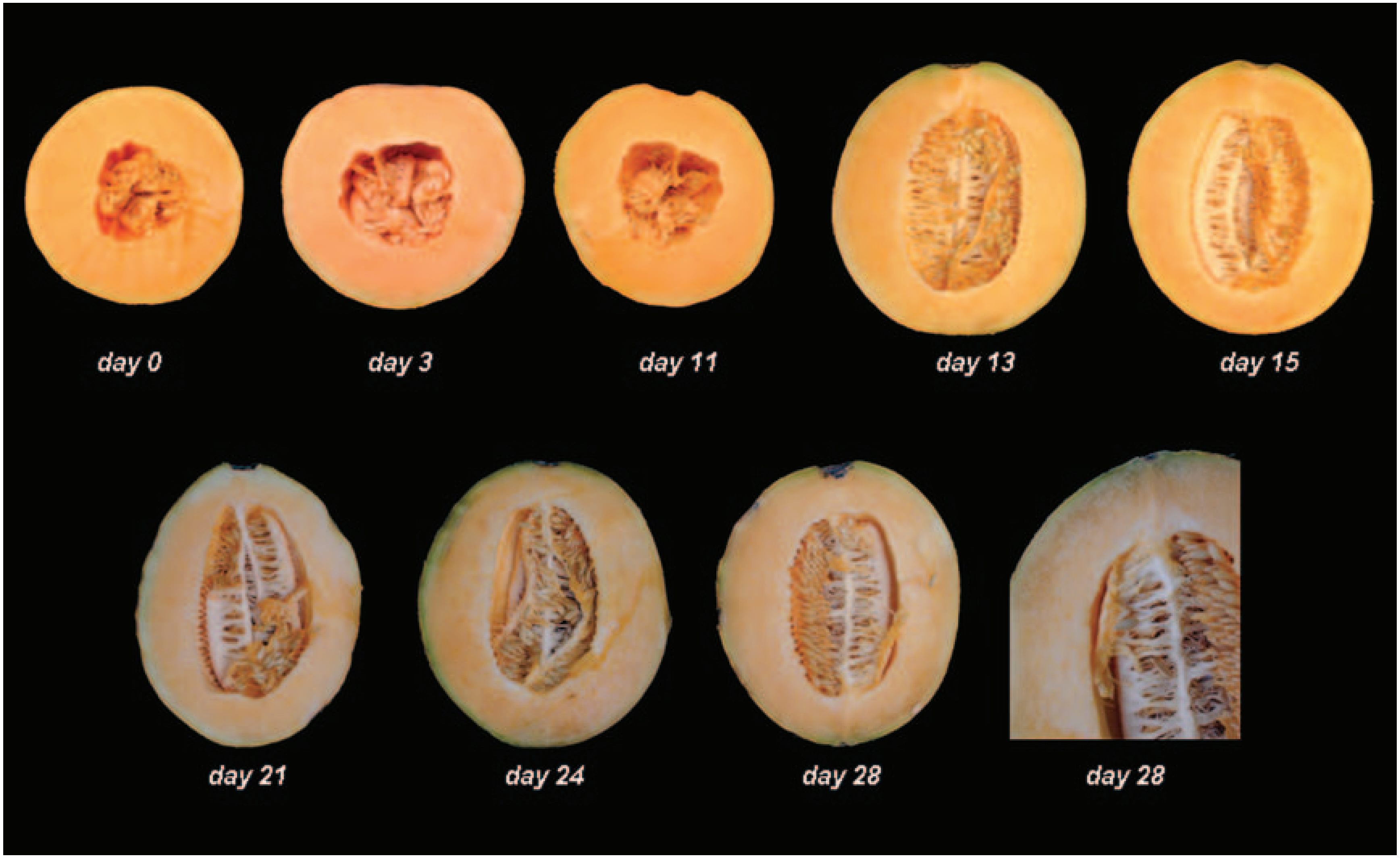
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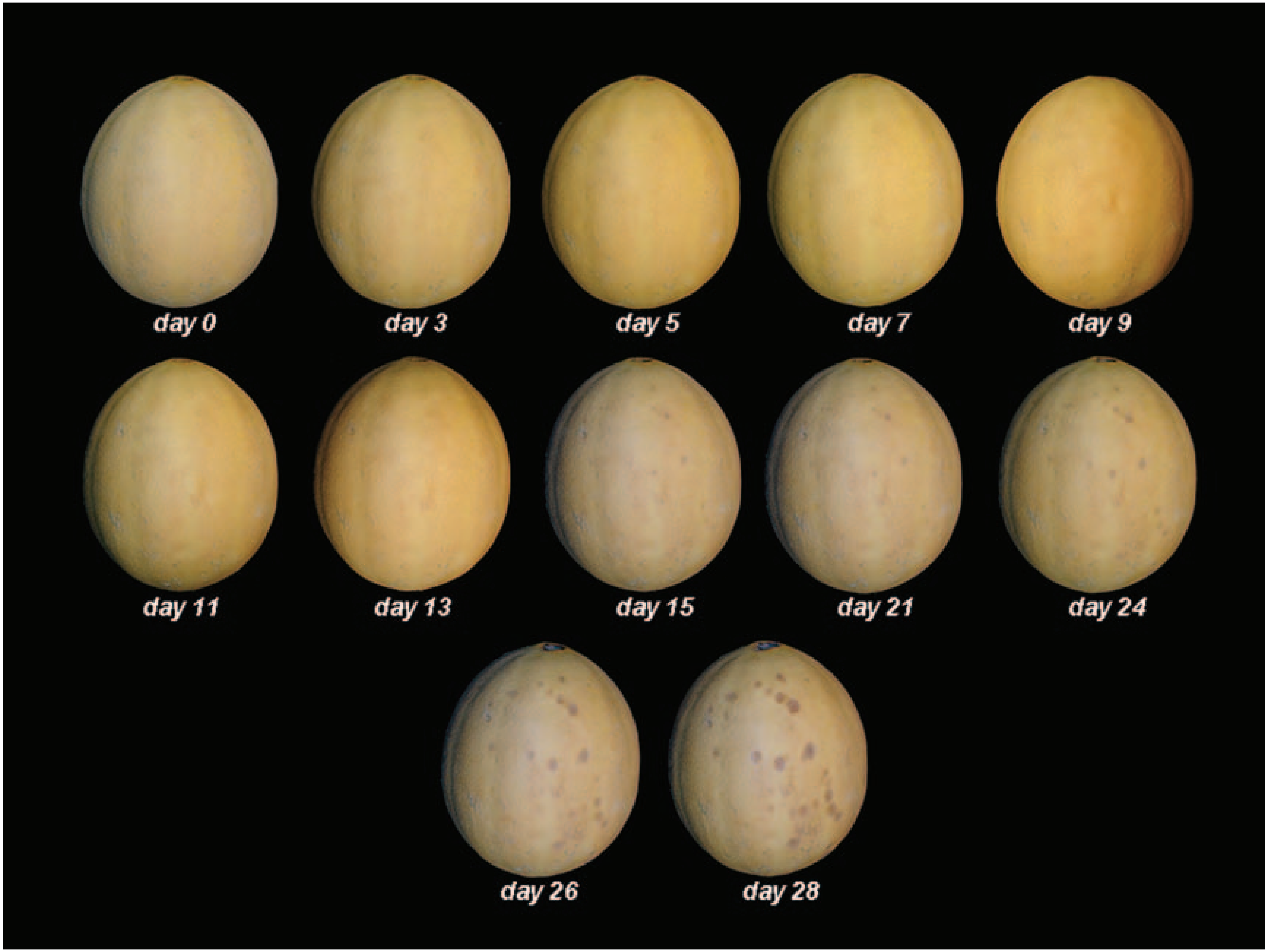
Figure 4.4. Internal symptoms of CI in 'Athena' cantaloupe stored at 0°C after transfer to 20°C for 2 days. Water-soaking of the flesh becomes apparent after 15 days at 0°C plus 2 additional days at 20°C. Decay develops at the stem-end of the fruit after 21 days.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day 28

Figure 4.5. Appearance of 'Athena' cantaloupe stored for 28 days at 5°C. Cantaloupe maintains acceptable appearance during 13 days. After 13 days few small brownish areas develop on the rind, which increase in number and size as storage progresses. Decay at the stem-end of the fruit is also noticeable after 26 days.

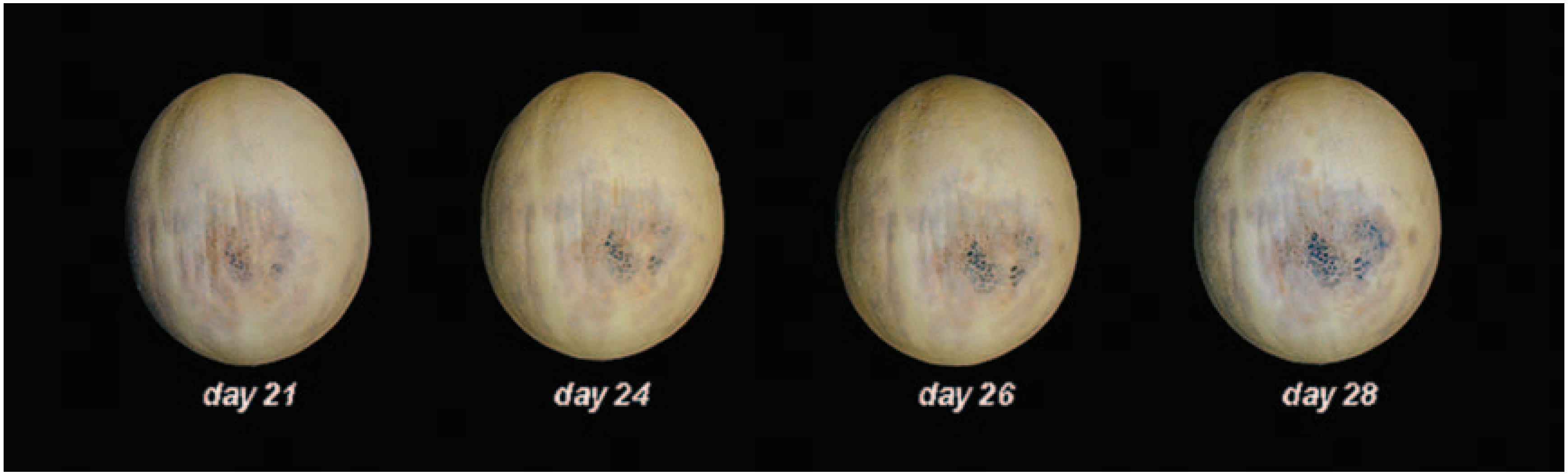
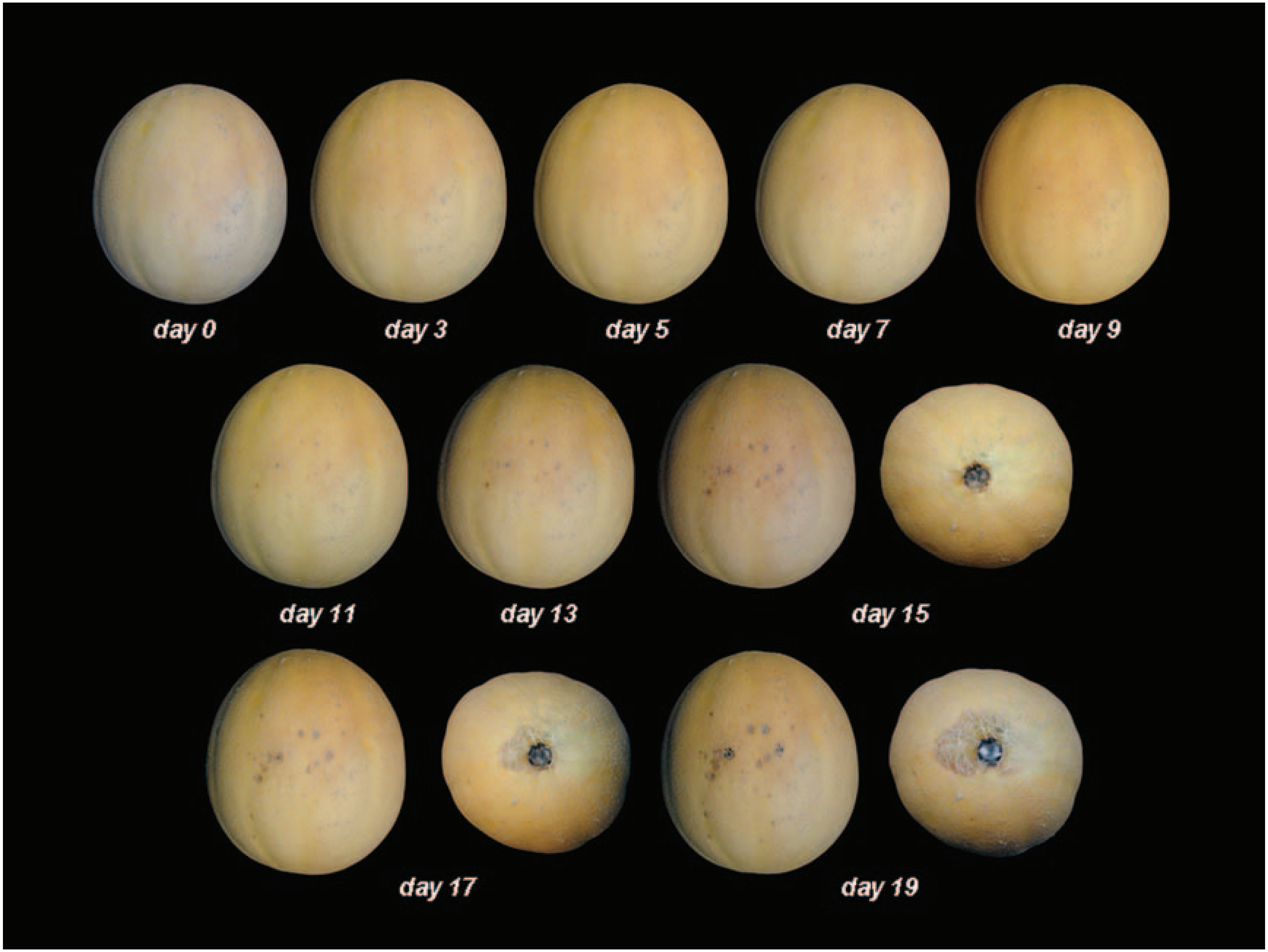


Figure 4.6. Appearance of ‘Athena’ cantaloupe stored for 28 days at 5°C (view of the area that rested on the ground). After 21 days the area of the melon that touched the ground deteriorates, the rind develops a shriveled, sunken, and greenish-yellow appearance, and after 28 days the affected area of the fruit is extremely decayed.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day 17
day 19

Figure 4.7. Appearance of ‘Athena’ cantaloupe stored for 19 days at 10°C. Cantaloupe maintains acceptable appearance during 13 days. After 13 days, few small brownish areas develop on the rind, which increase slightly in number and size as storage progresses. Decay starts to develop at the stem-end of the fruit after 15 days, and after 19 days the area around the stem-end is completely decayed.

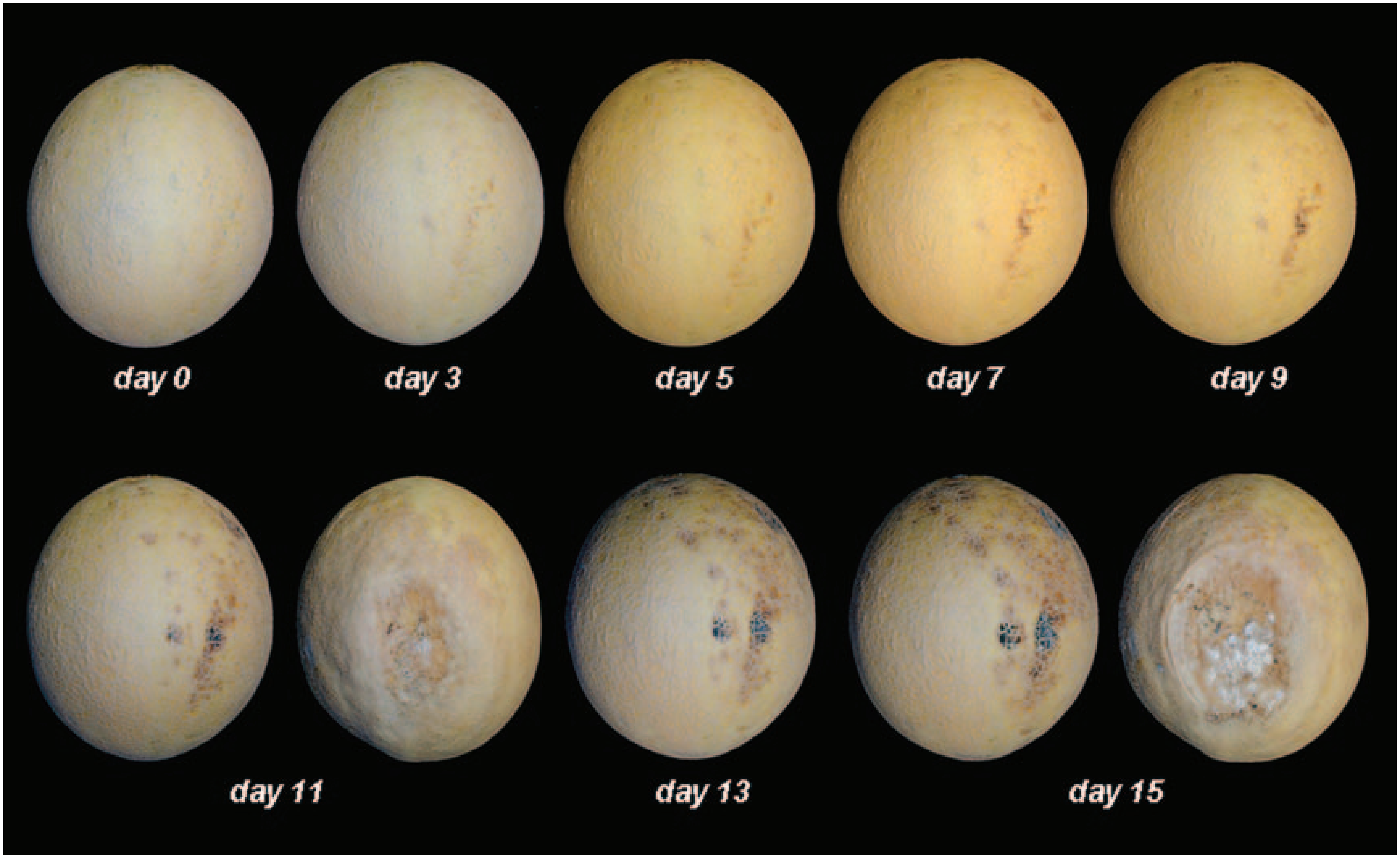


Figure 4.8. Appearance of 'Athena' cantaloupe stored for 15 days at 15°C. Color of cantaloupe changes from yellowish-green to yellow after 3 days, yet the fruit develops some brownish areas on the rind that result in severe decay after 15 days. After 11 days the area of the melon that touched the soil deteriorates and appears severely decayed after 15 days.

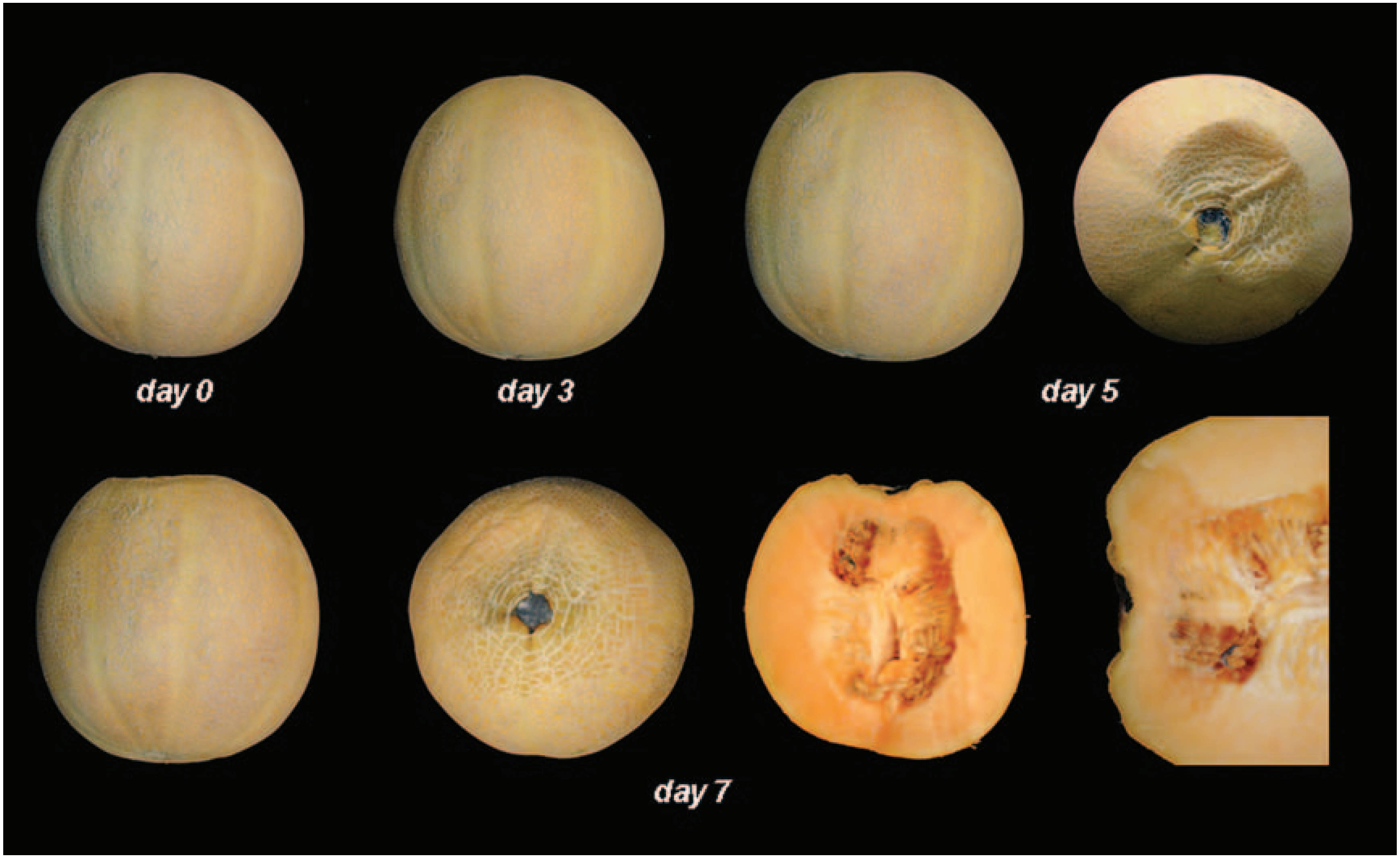


Figure 4.9. Appearance of 'Athena' cantaloupe stored for 7 days at 20°C. Cantaloupe maintains an acceptable appearance during 3 days. On day 5, decay develops at the stem-end, and after 7 days the top portion of the fruit around the stem-end collapses due to severe decay.

WATERMELON

Scientific Name: *Citrullus lanatus* var. *lanatus*
Family: Cucurbitaceae

Quality Characteristics

Watermelon is native to Africa, and it has been cultivated in the Middle East for thousands of years. Watermelon is a warm-season crop and is grown worldwide, usually in regions that have a long warm growing season. The fruit develops on trailing vines that may reach more than 5 meters in length; it is greatly appreciated for its thirst-quenching properties and attractive color (Snowdon 1990). There are many watermelon cultivars that vary in shape, color of the rind, and flesh, and some are seeded and others seedless. The shape of the fruit varies from globular to oblong, whereas the color of the rind varies in shades of green from a pale yellowish-green to a deep blackish-green. The pattern of the rind may also be solid, stripped, or marbled. Watermelon has a thin, firm external rind, a layer of white-fleshed internal rind that varies in thickness, and an interior edible flesh. Seeded watermelons have dark brown or black oval seeds, whereas seedless varieties may contain no seeds at all or only very small and thin, jelly-like white seeds. The color of the flesh varies from yellow, orange, pink, or red in most commercial varieties (Rushing 2004). Recently, smaller-sized watermelons (i.e., icebox-type) tend to have a higher acceptance by the consumers than large-sized melons because they are easier to handle and store (Sargent 2000). Seedless watermelon cultivars have also become popular, and studies indicated a slight eating quality preference for seedless watermelons compared to seeded cultivars (Marr and Gast 1991).

Watermelon maturity quality is not easy to determine visually, but some indices may help to determine if the fruit has attained the proper harvest maturity. When watermelon reaches horticultural maturity, the area of the fruit that rests on the ground (i.e., ground spot) changes from white to a creamy yellow, the vine tendrils proximal to the stem-end attachment become wilted and brown, but not fully desiccated, and the fruit surface may become irregular and dull rather than bright or glossy. In addition, when the resonance response heard upon impacting the fruit with the knuckles sounds dull or hollow rather than metallic, the watermelon is considered ready to harvest (Rushing 2004; Suslow 2006). Internal maturity quality indices for red watermelon varieties include sweet, crisp flesh and dark red color in red-fleshed cultivars. Sweetness usually develops simultaneously with changes in the color of the ground spot, decline in rind gloss, and increase in flesh color, whereas flesh crispness is associated with high moisture content (Corey and Schlimme 1988; Nip et al. 1968; Sargent 2000). In seeded watermelons, maturity is reached when the gelatinous covering around the seed is no longer apparent and the seed coat is hard (Suslow 2006). Overall, high-quality watermelons should be well formed with a uniform shape and a waxy, bright appearance, and the melons should appear heavy for size (Rushing 2004; Suslow 2006). Watermelon internal color and flavor may improve after harvest, but the fruit should be harvested at or near the fully mature stage. If harvested immature, watermelon will not develop good internal color and flavor (Mayberry et al. 1996; Sargent 2000; Suslow 2006).

In addition to changes in the external and internal visual quality attributes, sugar content of watermelon should also be considered as an indicator of fruit maturity and quality, because while seed and flesh coloration may continue to intensify following harvest, sugar content tends to decrease (Elmstrom and Davis 1981). Soluble solids, total sugars, and sucrose, fructose, and glucose contents of watermelon depend upon several factors including the area of production, field temperatures during development, cultivar, maturity at harvest, and also the portion of the flesh within the fruit (Brown and Summers 1985; Elmstrom 1971; Elmstrom and Davis 1981a, 1981b; Gilreath et al. 1986; Kano 2004; Pardo et al. 1997; Showalter 1975).

Soluble solids content increases during fruit development from 3.3 to 4% in immature fruit to about 11–13% in mature watermelon, and then decreases in overripe fruit (Corey and Schlimme 1988; Nip et al. 1968). At the fully ripe stage, soluble solids content of small watermelons (i.e., icebox-type, fruit with an average weight of about 2–7 kg) grown in Florida and South and North Carolina ranged from 11.0 to 12.4%, which is well above the standard for very good quality watermelon (Gilreath et al. 1986; Schulthesis et al. 2007), whereas soluble solids content in traditional large watermelon cultivars may vary between 7.4 and 11.3% (Elmstrom 1971; Showalter 1975). Seedless watermelon cultivars grown in Spain were reported to have higher soluble solids content (11–11.4%) than small or large watermelon cultivars (9.1–10.8% and 9.6–9.7% soluble solids content, respectively) (Pardo et al. 1997). In addition to cultivar variations, the middle portion of the flesh within the melon was also reported to have higher soluble solids content than the flesh at the stem or blossom ends (Showalter 1975). Nevertheless, a soluble solids content of 10% in the flesh near the center of the fruit is usually accepted as an indicator of very good watermelon maturity quality (Gilreath et al. 1986; Suslow 2006).

Fructose and glucose are the predominant sugars in immature watermelon; the content increases during fruit development until about 20–36 days after anthesis and then decreases in fully mature fruit (36–48 days after anthesis, depending on the cultivar). Sucrose, however, was not evident before 20–24 days after anthesis, but thereafter sucrose content increases rapidly, becoming the main sugar in fully mature fruit. Total sugar content increases until 32 days after anthesis and then decreases slightly in fully mature fruit (Brown 1985; Elmstrom and Davis 1981a, 1981b). Total sugar content was higher in seedless watermelon cultivars, ranging from 8.8 to 9.69% compared to small or large seeded watermelon cultivars (7.70–9.19% and 7.55–7.67%, respectively). Sucrose content was higher in 'Sugar Baby' and 'Sugar Bell' watermelons, and represented 30% of the total sugars, whereas glucose was higher in seedless cultivars, representing 46% of total sugars. In large watermelon cultivars, glucose represented 24% of the total sugars (Pardo et al. 1997). Sweetness of watermelon depends on the proportion of sugars present in the flesh at the eating stage. Because the relative sweetness of fructose is greater than that of sucrose, watermelons with a higher content of fructose than sucrose would have higher sweetness. In general, flesh sweetness increases until 32 days after anthesis and then decreases in overripe fruit. Development of early sweetness is considered to be important in the production of high-quality watermelons that are harvested before full maturity for long-distance markets (Elmstrom and Davis 1981a, 1981b). Seedless and small watermelon cultivars were in general sweeter than large cultivars owing to their higher sugar content (Pardo et al. 1997). Furthermore, lower fruit temperatures during development in the field were associated with higher sugar content and thin rind. Shaded watermelon had higher sugar content and a thinner rind than fruit grown under full sun exposure. During fruit development on the plant, temperatures below 35°C resulted in less sugar consumption and higher lycopene production, whereas temperatures of 40°C or higher increased fruit respiration rate, and thus sugar consumption (Kano 2004).

Watermelon is a relatively good source of potassium, vitamin C, and provitamin A, or β-carotene, and an excellent source of lycopene. In watermelon, lycopene is the major pigment of the total pigment content (73.7–97%) followed by β-carotene (4.1–5%) (Lewinsohn et al. 2005; Morgan 1967; Perkins-Veazie and Collins 2006). Lycopene content increases as the fruit ripens, and then either remains constant or decreases in overripe fruit. In fully ripe fruit, lycopene content was 20% and 10% higher than in underripe and overripe fruits, respectively. Seedless watermelons tended to have higher amounts of lycopene, fructose, and glucose than seeded watermelons (Bang et al. 2004; Jaskani et al. 2005; Leskovar et al. 2003, 2004; Perkins-Veazie et al. 2001, 2006, 2007). Although red-fleshed watermelon cultivars are very rich in lycopene (32.5–120.5 mg/kg fresh weight), yellow and orange-fleshed watermelon cultivars have less than 0.3 mg/kg or about 5 g of lycopene per kilogram of fruit fresh weigh, respectively, and most of the carotenoid content is β-carotene (Perkins-Veazie et al. 2001, 2006, 2007; Tadmor et al. 2005). White watermelon cultivars contain less than 0.1 mg of lycopene per kilogram of fruit fresh weight (Perkins-Veazie et al. 2007).

Watermelon contains on average 91% water, 0.6% protein, 7.6% carbohydrate, 0.3 to 0.4% fiber, 112 mg of potassium, 2.7–10 mg of vitamin C, 295–303 μg of β-carotene, 569 IU of vitamin A, 3,400–10,000 μg of lycopene, and 130–310 μmol of total phenols per 100 g fruit fresh weight (Floyd and Fraps 1939; Gil et al. 2006; Holden et al. 1999; Leskovar et al. 2004; Perkin-Veazie and Collins 2003; Perkins-Veazie et al. 2001, 2006; USDA 2006; Vanderslice et al. 1990; Vidal-Valverde et al. 1982; Vinson et al. 2001).

Optimum Postharvest Handling Conditions

Watermelons usually are not pre-cooled and are often shipped and displayed at the retail market without refrigeration (Risse et al. 1990; Sargent 2000; Suslow 2006). However, when possible, watermelons should be pre-cooled prior to storage using forced-air cooling. If room-cooled, good air circulation between the pallets is necessary to remove field heat (Rushing 2004). If pre-cooling is unavailable, watermelon should be promptly stored at 10–15°C with a relative humidity of 85–90%. Under recommended storage conditions expected postharvest life of watermelon is about 2 weeks at 10°C and 3 weeks at 15°C (Mayberry et al. 1996; Risse et al. 1990; Rushing 2004; Sargent 2000; Suslow 2006). Higher humidity levels combined with temperatures above 15°C may promote decay at the stem-end, while temperatures lower than 10°C may result in chilling injury (Risse et al. 1990; Sargent 2000).

Exposure of watermelon to ethylene during storage should be avoided as that may result in fruit softening and increased water-soaking of the flesh and rind. Storage of watermelon for 3–9 days at 18 or 20°C with ethylene levels between 1 and 50 μl/liter resulted in membrane disruption, increased electrolyte leakage, decline in flesh firmness and water-soaking of flesh and rind, off-odors, and increased pathogen proliferation at the stem- and blossom-ends (Elkashif and Huber 1988; Elkashif et al. 1989; Mao et al. 2004; Risse and Hatton 1982).

Temperature Effects on Quality

Postharvest life and quality of watermelons are determined by the environmental conditions following harvest, particularly temperature. Watermelons are often shipped without refrigeration, which may contribute to accelerated loss of quality (Risse et al. 1990; Suslow 2006). In an early study, 5% of the total watermelons shipped to the New York market from Florida, Texas, and Mexico showed diseases, physiological disorders, or mechanical injury. Diseases accounted for 40%, physiological disorders for 20%, and injuries for 40% of fruit defects. Stem-end rot, anthracnose, blossom-end rot, black rot, bacterial soft rot, and *Rhizopus* rot were the most common pathogens encountered, whereas overripe and soft fruit were the most prevalent physiological disorders reported (Cappellini et al. 1988).

Firmness of watermelons declines during storage, even when the fruit is stored within the optimum recommended temperatures. For example, firmness of watermelons declined by 11 and 25% after storage for 7 and 13 days at 13°C, respectively, whereas after 21 days, firmness declined by 40% (Mao et al. 2004). Flesh firmness remained unchanged after storage of watermelons for 9 days at 18°C, whereas rind tissue firmness decreased by about 10% after 3 days, but no further changes were observed after 9 days of storage (Elkashif and Huber 1988). Although fruit firmness and rind thickness tend to decrease with increasing storage temperature, watermelon flesh becomes redder when fruit are exposed to temperatures between 13 and 37°C (Abaka-Gyenin and Norman 1977; Perkins-Veazie and Collins 2006; Picha 1988; Risse et al. 1990; Showalter 1960; Vogele 1937). However, when exposed at lower temperature some fading of the red color was observed (Abaka-Gyenin and Norman 1977; Picha 1988; Showalter 1960). After storage for 1 or 4 weeks at temperatures between 22 and 34°C, watermelon internal color becomes redder, whereas fruit stored at 10°C was not as red as it was at harvest (Showalter 1960). Likewise, watermelon flesh from three different cultivars was darker (lower L* values) and redder (higher a* values) after storage for 14 days at 21°C compared to storage at 5 or 13°C. In fact, flesh of watermelon stored at 5 or 13°C was less red after storage than fresh watermelon (Perkins-Veazie and Collins 2006). Increase in red color intensity during storage of watermelons at high temperatures was attributed to increased synthesis of lycopene (Collins et al. 2006; Perkins-Veazie and Collins 2003, 2006).

Although exposure of watermelons to temperatures above the optimum will result in accelerated loss of firmness and development of decay, holding watermelons at temperatures lower than the optimum will result in CI. For example, watermelons held for more than 7 days at 7°C may develop CI when subsequently exposed to typical retail conditions (Risse et al. 1990; Perkins-Veazie and Collins 2003; Suslow 2006). Symptoms of CI are characterized by surface pitting and brown-staining of the rind, deterioration of flavor, and fading of flesh color. When transferred to ambient temperatures, the symptoms of CI aggravate, and the pits in the rind will be invaded by decay-causing organisms, mainly black rot (Mayberry et al. 1996; Rushing 2004; Sargent 2000; Suslow 2006). Storage of watermelons for 9 days at 14°C resulted in the maintenance of good visual quality, whereas visual quality of watermelons stored at 5°C decreased during storage. Flesh of watermelons stored at 5°C darkened and developed slight water-soaked areas, owing to CI (Gil et al. 2006). Symptoms of CI in watermelons stored at 0°C appeared randomly over the entire fruit surface, equally severe between the distal and proximal ends, and between the stem- and blossom-ends, but were more severe in areas of superficial abrasion. Brown-staining of the rind was the primary symptom of chilling, followed by rind-pitting in severely injured watermelons after storage at 0°C, and the symptoms intensified during subsequent holding periods of 4 and 8 days at 21°C. Symptoms of CI were less severe in watermelons stored at 7°C than at 0°C, and no brown-staining or rind-pitting occurred in fruit stored at 16°C and subsequently held at 21°C (Picha 1986, 1988). Decrease in pigment content and redness of the flesh was also attributed to CI in watermelon stored at 10 or 2°C (Showalter 1960). Watermelon cultivars vary in their susceptibility to CI, and, for example, ‘Baby Fun’ was reported to be more susceptible than either ‘Michylee’ or ‘Minilee’ fruit during storage for 3 weeks at 1°C (Risse et al. 1990). Based on feasibility testing, conditioning watermelons at 26°C for about 3–4 days prior to storage at 0 or 7°C induces some tolerance to chilling temperatures but does not completely alleviate the injury (Picha 1986; Risse et al. 1990). Conditioning of small watermelons for 3 days at 26°C prior to cold storage reduced the incidence and severity of CI and increased the percentage of marketable fruit for storage at 1°C (Risse et al. 1990).

Compositional changes were also observed in watermelons stored at different temperatures. For example, with increased storage temperature total soluble solids content of watermelon cultivars decreased, whereas pH increased (Perkins-Veazie and Collins 2003, 2006; Risse et al. 1990). Sucrose, glucose, and fructose contents did not change in ‘Charleston Gray’ and ‘Jubilee’ watermelons after storage for 14 days at 0°C plus 5 days at 23°C, yet soluble solids content in ‘Jubilees’ decreased. However, fructose, glucose, and soluble solids contents declined after storage for 19 days at 23°C (Picha 1988). Storage of watermelons for 14 days at 20°C resulted in a significant decrease in pH and soluble solids and total sugar contents (Radulović et al. 2007).

Lycopene content of watermelons continues to increase during storage, and synthesis is accelerated when storage temperature increases. Lycopene content of ‘Black Diamond,’ ‘Summer Flavor 800,’ and ‘Sugar Shack’ stored at 13°C was similar to that of fresh watermelons after 14 days of storage, whereas in melons held at 5°C lycopene content decreased by 12–24%. Conversely, lycopene content increased by 12–40% in fruit stored at 21°C, compared to fresh watermelons (Perkins-Veazie and Collins 2003, 2006). Similarly, whole watermelons stored either at 5 or 13°C lost about 6–10% of lycopene content after 2 weeks, but due to accelerated carotenoid synthesis gained as much as 20% total lycopene after storage at 21°C (Perkins-Veazie et al. 2007). As storage temperature was raised from 20 to 37°C, lycopene content of watermelons continued to increase, regardless of the temperature (Vogele 1937). Although lycopene content of watermelons stored at 5°C was slightly reduced after 9 days, no degradation of ascorbic acid or total phenolics was observed (Gil et al. 2006).

Time and Temperature Effects on the Visual Quality of 'Sugar Baby' Watermelons

'Sugar Baby' watermelons (small seeded cultivar) shown in Figures 4.10–4.19 were harvested at the full mature stage with an average weight of 2–3 kg, from a commercial operation in Saint-Augustin-de-Desmaures, Quebec, Canada, during the summer season (i.e., early September). Promptly after harvest, fresh watermelons were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Visual quality attributes of 'Sugar Baby' watermelons change during storage. Major visual changes during storage of watermelons at temperatures below 5°C are related mainly to CI. In watermelons stored at temperatures above 5°C, changes in the color of the rind from dark green to very dark green, flesh dryness, and discoloration are the major visual changes observed during storage.

'Sugar Baby' watermelons stored at 0°C maintained acceptable external visual quality during 28 days, but few small depressions on the rind are noticeable at this time. After 28 days, the flesh of the fruit near the rind at the blossom-end appears water-soaked and leaky (Figure 4.10). When watermelons stored at 0°C are transferred to 20°C for 2 additional days, pitting and brown-staining of the rind aggravates, and after 20 days the fruit shows some brown-staining in the ground spot area; after 24 days pitting is evident is some areas of the rind and spreads to the whole fruit surface after 28 days. After 28 days the watermelon appears extremely pitted and some decay develops in the sunken areas of the rind (Figure 4.11). Watermelons maintain acceptable internal visual quality during 24 days at 0°C plus 2 additional days at 20°C, but after 28 days water-soaking of the flesh is evident (Figure 4.12).

Although watermelons stored at 5°C maintained an acceptable external visual quality for 32 days, pits developed on the rind of fruit stored for 36 days at 5°C, whereas the flesh appears somewhat leaky and spongy (Figure 4.13). Upon transfer to 20°C for 2 additional days, symptoms of CI aggravate, becoming extremely severe after 36 days at 5°C plus 2 days at 20°C. Pits on the rind appear after 22 days, pitting and brown-staining on the ground spot area become evident after 32 days, and after 36 days the fruit is severely affected by pitting. The size and number of lesions increase and the sunken areas are invaded by decay pathogens (Figures 4.14 and 4.16). Simultaneously, red color of the flesh fades slightly, and after 28 days the flesh appears less red than at the time of harvest (day 0). In addition, after 28 days at 5°C plus 2 days at 20°C, watermelon flesh appears soggy with areas of water-soaking (Figure 4.15).

External visual quality of 'Sugar Baby' watermelons remains acceptable during 36 days at 10°C, yet the pedicle still attached to the stem-end of the fruit appears dry and shriveled. Rind color changes during storage from a dark green to a very dark green, and after 36 days the watermelon rind appears very dark green, whereas the flesh develops a soggy and discolored appearance (Figure 4.17).

After 36 days at 15°C watermelon external rind appears more dark green than at the time of harvest, whereas the internal yellowish-white rind and flesh appear dry, woody, and discolored, yet the external appearance is still considered acceptable (Figure 4.18). Similar visual quality changes are noticed in watermelons stored at 20°C; however, changes occur more rapidly than at 15°C (Figure 4.19). Color of the rind changes during storage of 'Sugar Baby' watermelons at 20°C, and after 28 days the rind appears more dark green than at the time of harvest. Simultaneously, the internal rind and flesh develop a dry, mealy, and discolored appearance.

Overall, 'Sugar Baby' watermelons stored at 10 or 15°C maintain acceptable visual quality for longer periods compared to melons stored at 0, 5, or 20°C. Postharvest life of watermelons stored at 0 and 5°C is reduced to 20 and 22 days, respectively, owing to CI, whereas fruit stored at 10, 15, and 20°C maintains acceptable visual quality for 32, 36, and 28 days, respectively.

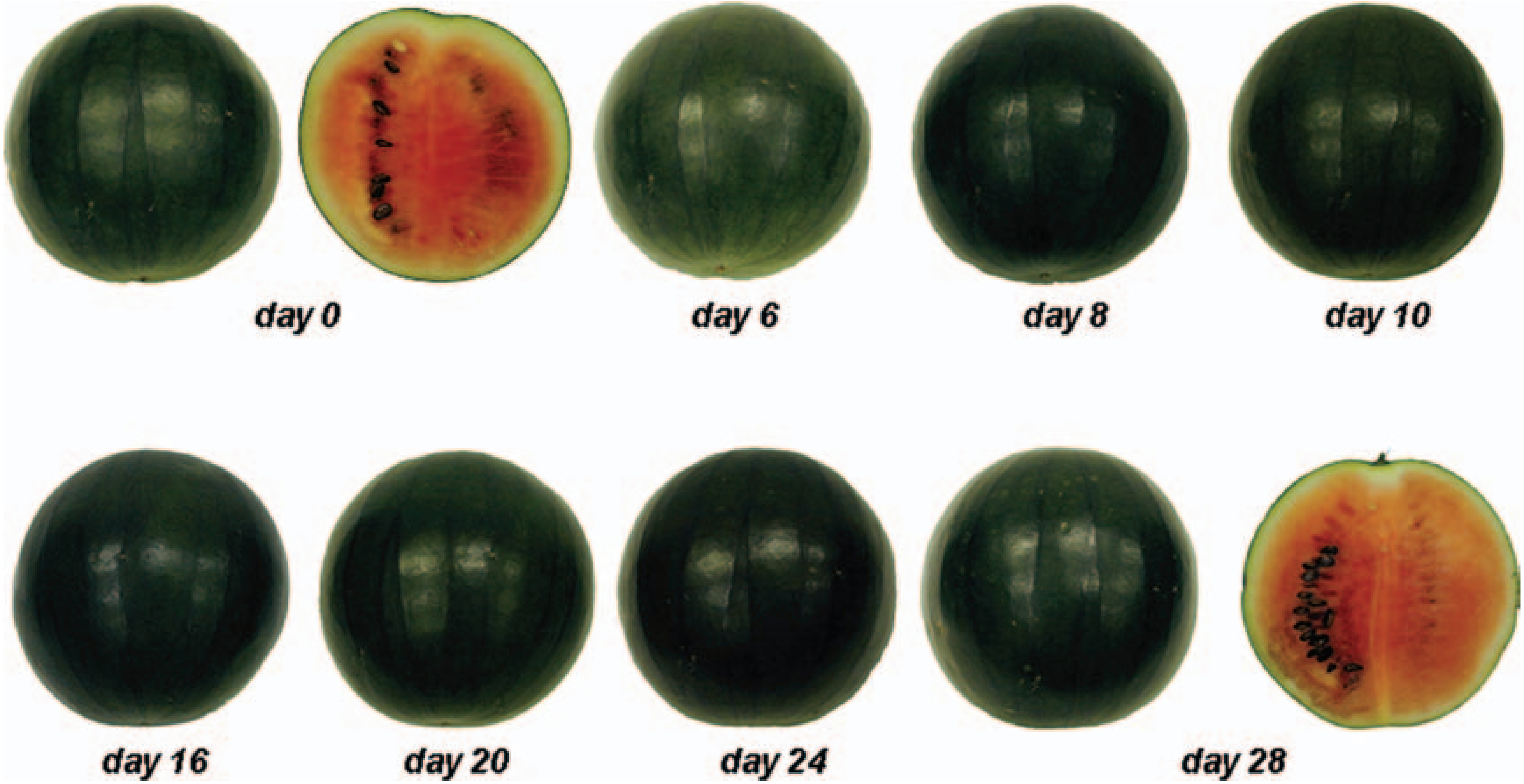

day 0
day 6
day 8
day 10
day 16
day 20
day 24
day 28

Figure 4.10. Appearance of ‘Sugar Baby’ watermelon stored for 28 days at 0°C. Watermelon maintains acceptable external appearance during 24 days, but after 28 days some pitting developed on the rind near the stem-end of the fruit. Simultaneously, some water-soaking of the flesh adjacent to the rind near the blossom-end of the fruit is noticeable.

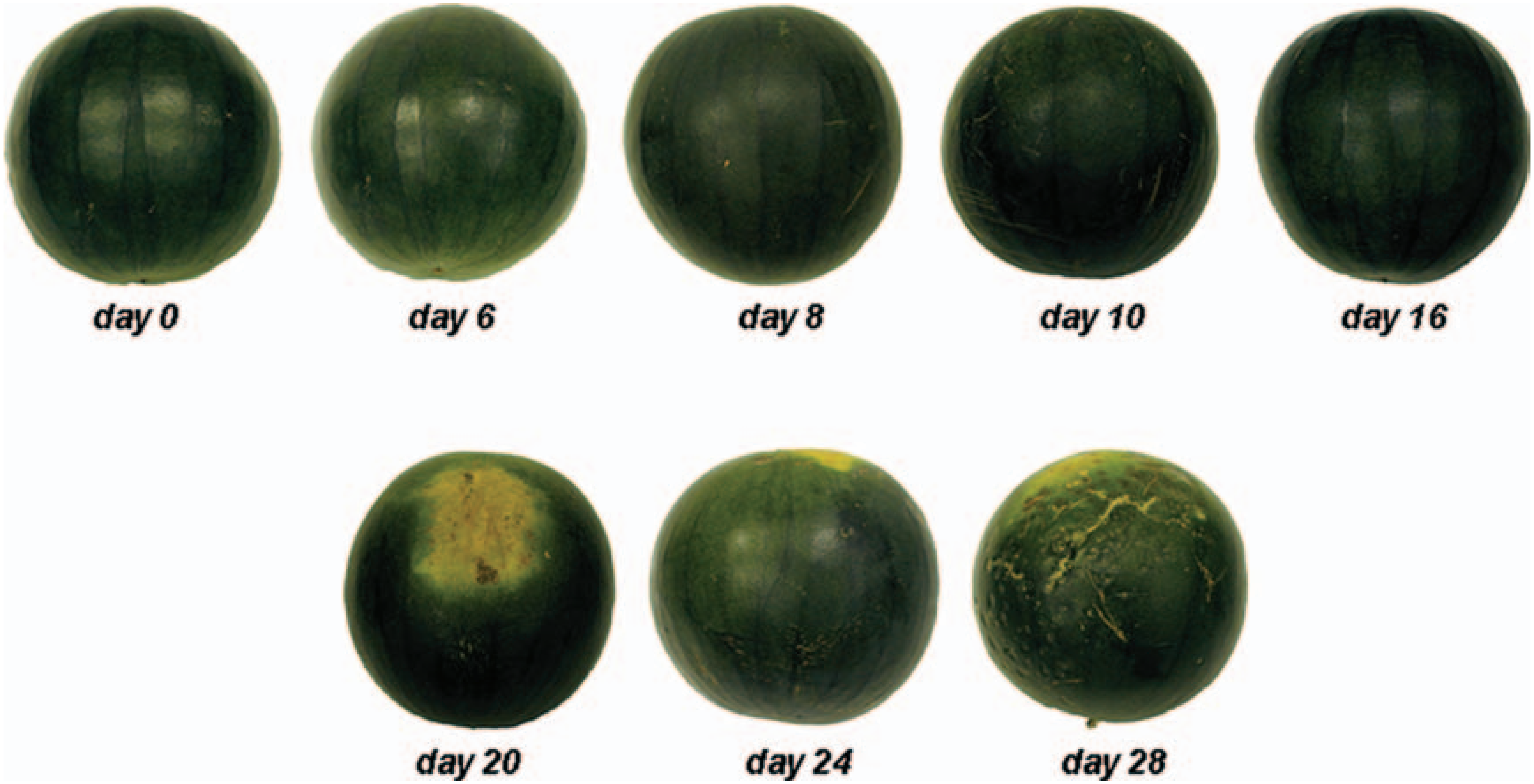


Figure 4.11. Chilling injury in 'Sugar Baby' watermelon stored at 0°C after transfer to 20°C for 2 days. Brown-staining is noticeable at the ground spot area after 20 days, and pitting develops in some areas of the rind in watermelon stored for 24 days at 0°C upon transfer to 20°C. Severity of pitting aggravates when fruit is stored for 28 days at 0°C plus 2 days at 20°C.

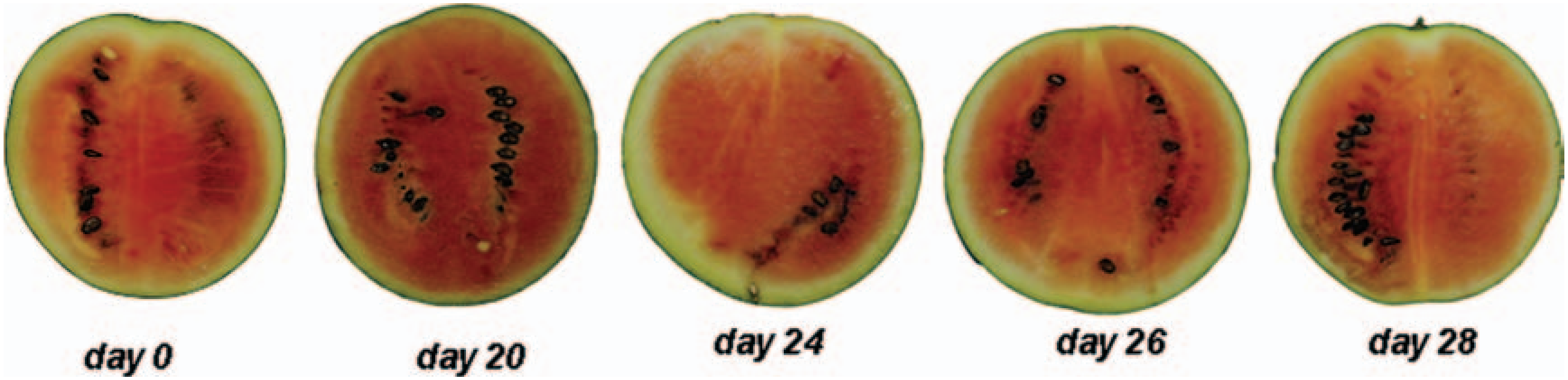


Figure 4.12. Internal appearance of 'Sugar Baby' watermelon stored at 0°C after transfer to 20°C for 2 days. Red color of the flesh fades slightly as storage progresses; after 28 days flesh appears less red than at the time of harvest and water-soaking is evident.

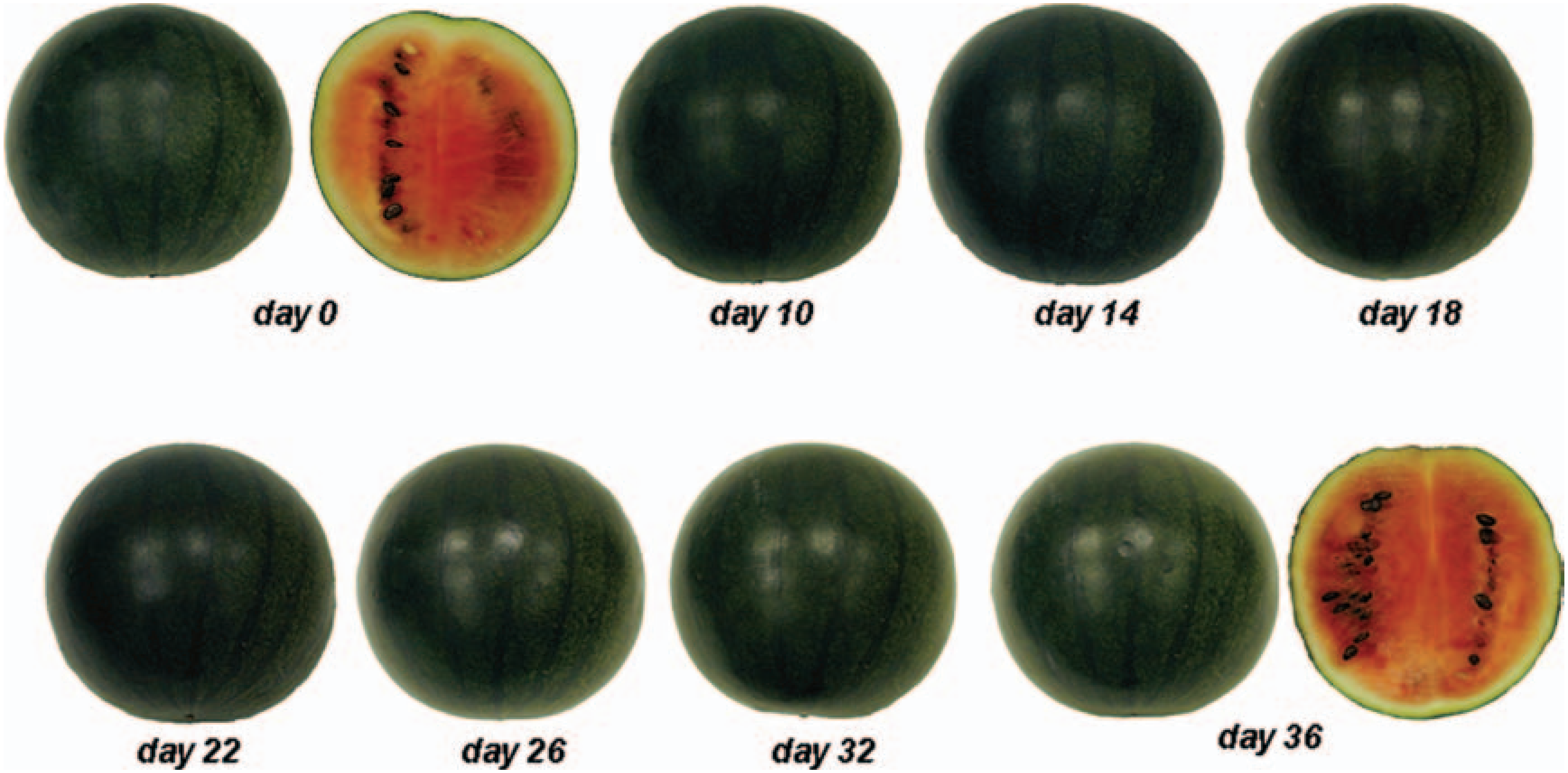

day 0
day 10
day 14
day 18
day 22
day 26
day 32
day 36

Figure 4.13. Appearance of 'Sugar Baby' watermelon stored for 36 days at 5°C. Watermelon maintains acceptable external appearance during 32 days, but after 36 days slight pitting develops on the rind. The flesh appears spongy with some areas of water-soaked tissue.

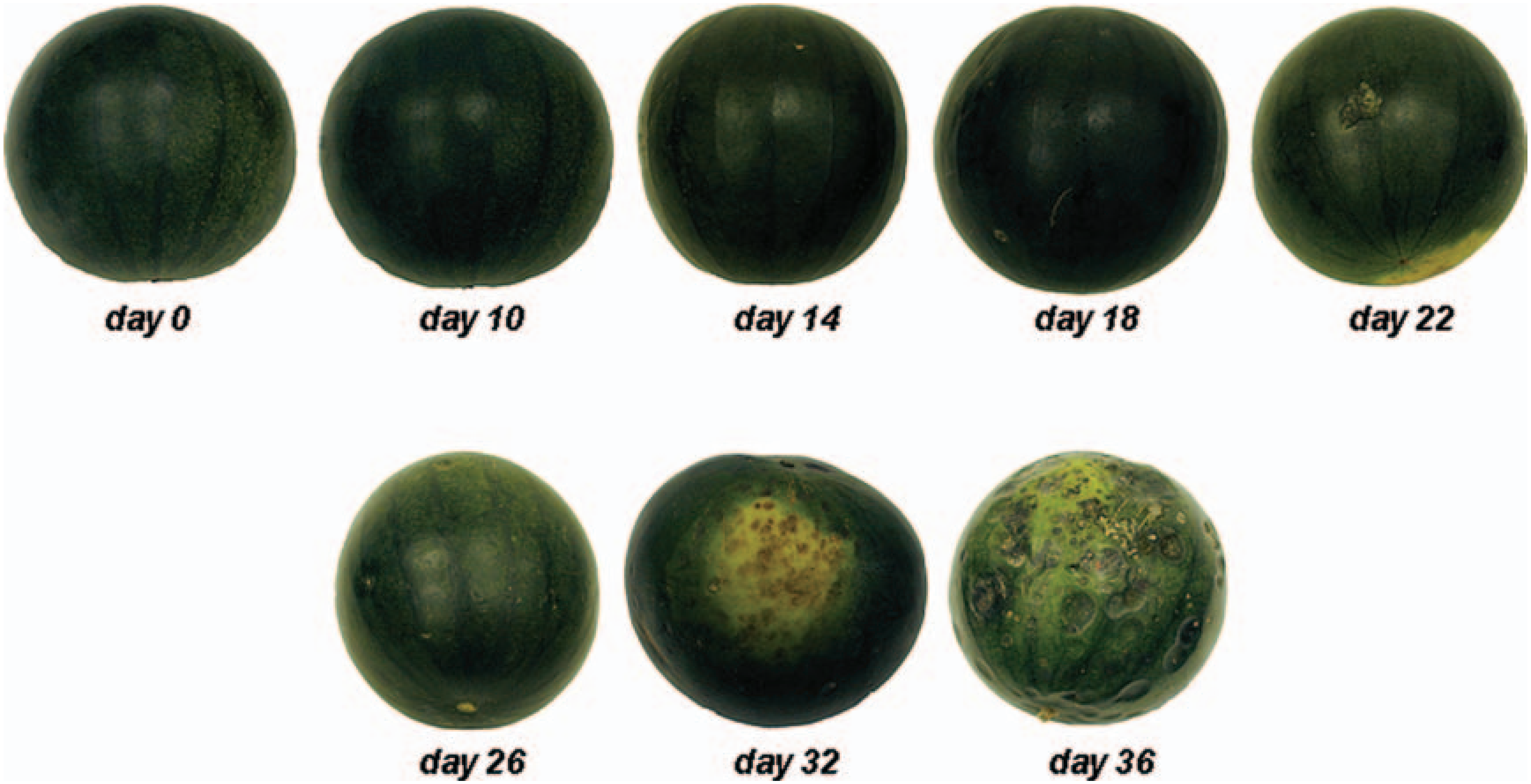

day 0
day 10
day 14
day 18
day 22
day 26
day 32
day 36

Figure 4.14. Chilling injury in 'Sugar Baby' watermelon stored at 5°C after transfer to 20°C for 2 days. Pitting of the rind develops upon transfer for 2 days to 20°C in some areas of the rind in watermelon stored for 22 days at 5°C. Severity of pitting aggravates as storage progresses; after 32 days brown-staining of the rind is evident at the ground spot, and after 36 days decay develops on the pits.

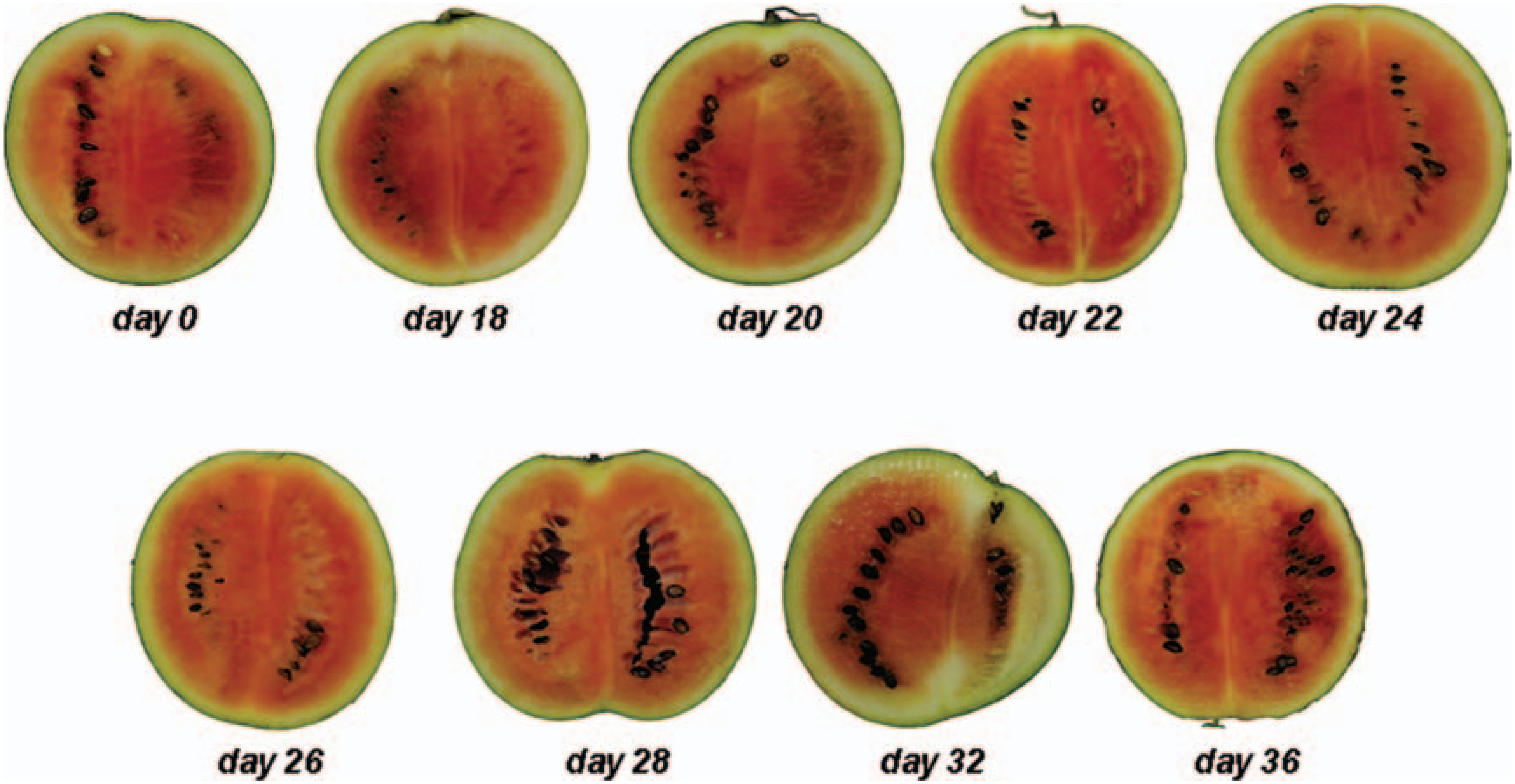

day 0
day 18
day 20
day 22
day 24
day 26
day 28
day 32
day 36

Figure 4.15. Internal appearance of 'Sugar Baby' watermelon stored at 5°C after transfer to 20°C for 2 days. Red color of the flesh slightly fades as storage progresses; after 28 days flesh appears less red than at the time of harvest and appears soggy with some areas of water-soaked tissue.

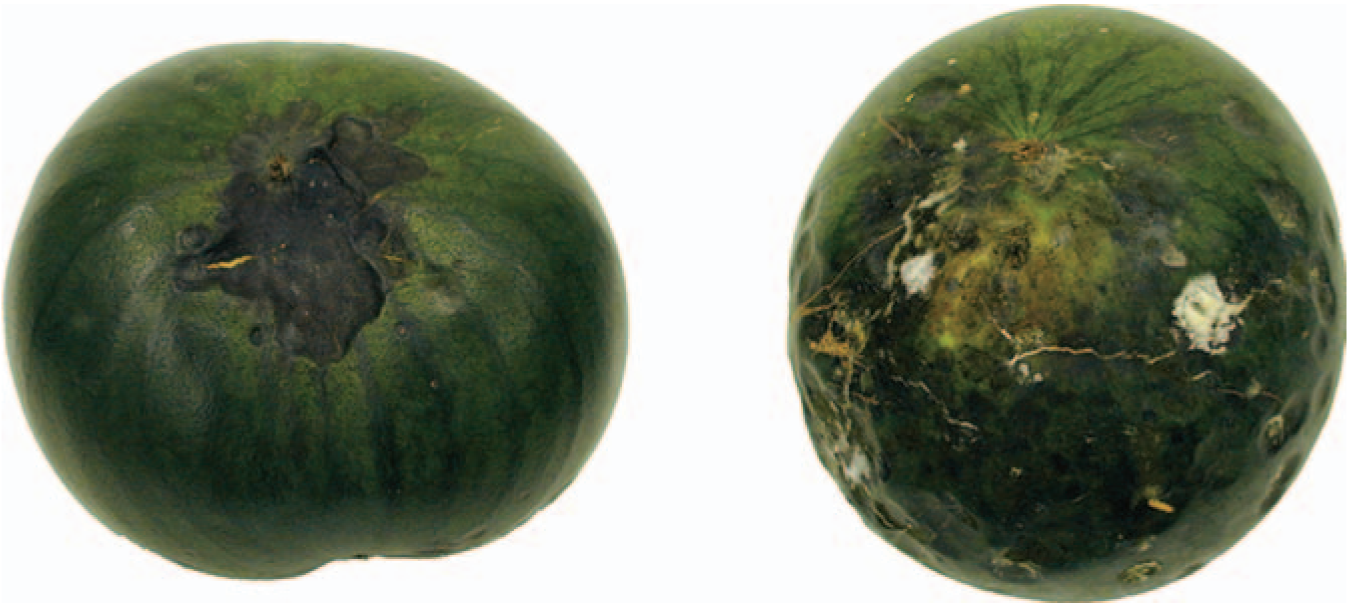


Figure 4.16. Chilling injury in 'Sugar Baby' watermelon stored at 0 and 5°C upon transfer to 20°C for 2 days. After 2 days at 20°C, a dark-brown, sunken, leathery lesion develops in melon exposed for 28 days at 0°C (left), and after 36 days pits are severely invaded by decay pathogens in melon exposed at 5°C (right).

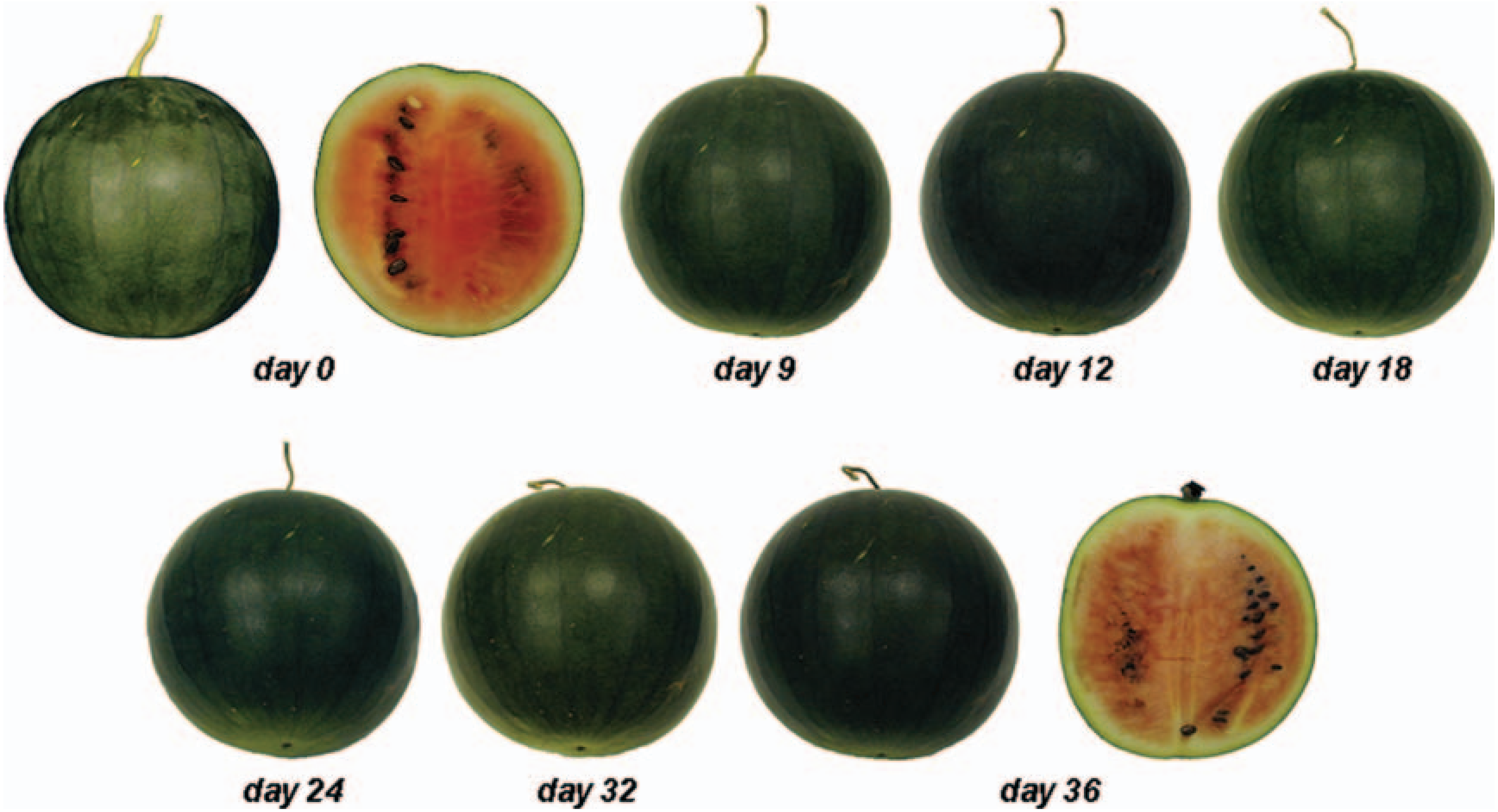

day 0
day 9
day 12
day 18
day 24
day 32
day 36

Figure 4.17. Appearance of ‘Sugar Baby’ watermelon stored for 36 days at 10°C. After 36 days the peduncle still attached to the stem-end appears dry and shriveled, and the watermelon flesh appears soggy and discolored compared to at the time of harvest.

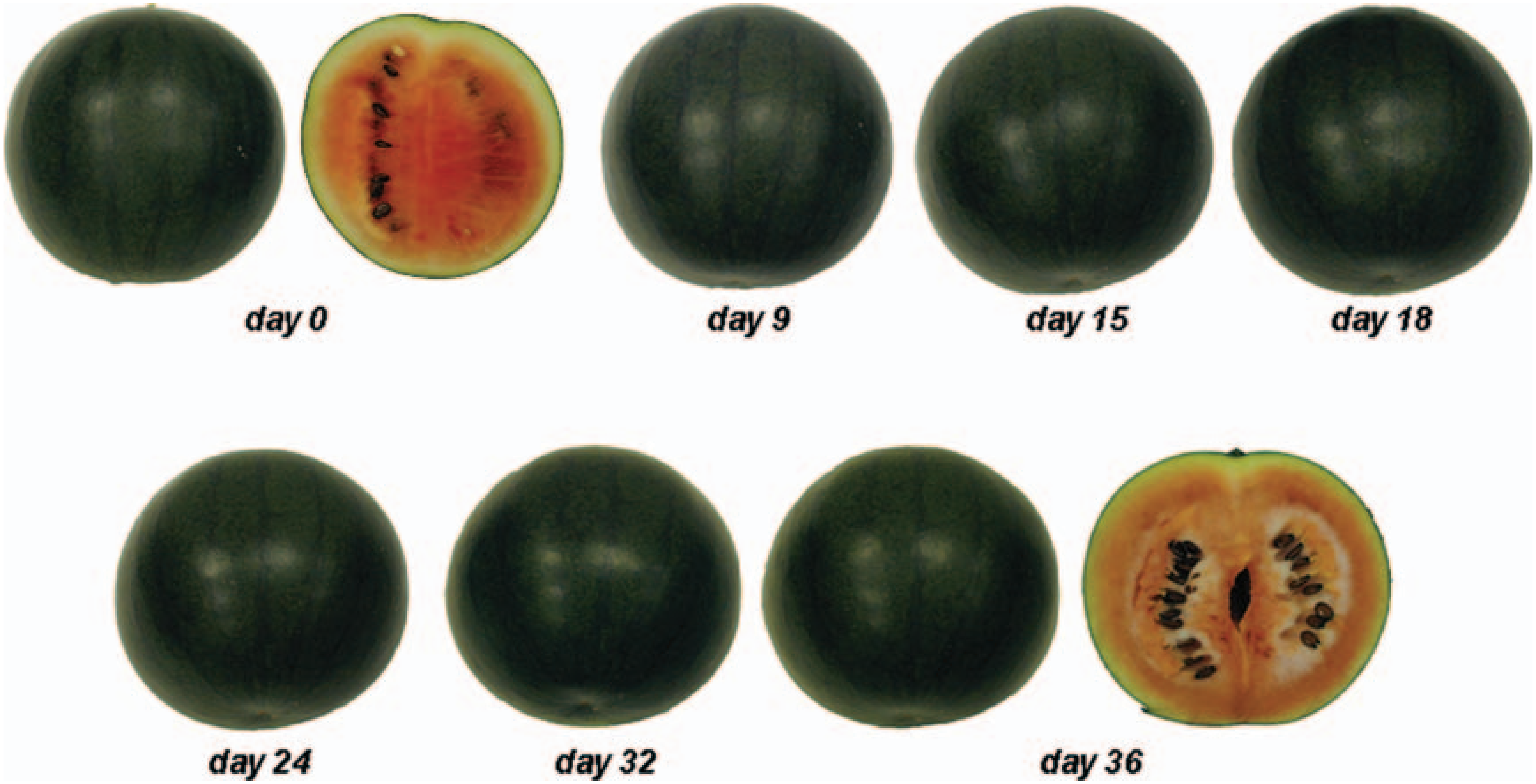

day 0
day 9
day 15
day 18
day 24
day 32
day 36

Figure 4.18. Appearance of 'Sugar Baby' watermelon stored for 36 days at 15°C. After 36 days the watermelon rind appears more dark-green and the internal rind and flesh appear dry and discolored compared to at the time of harvest.

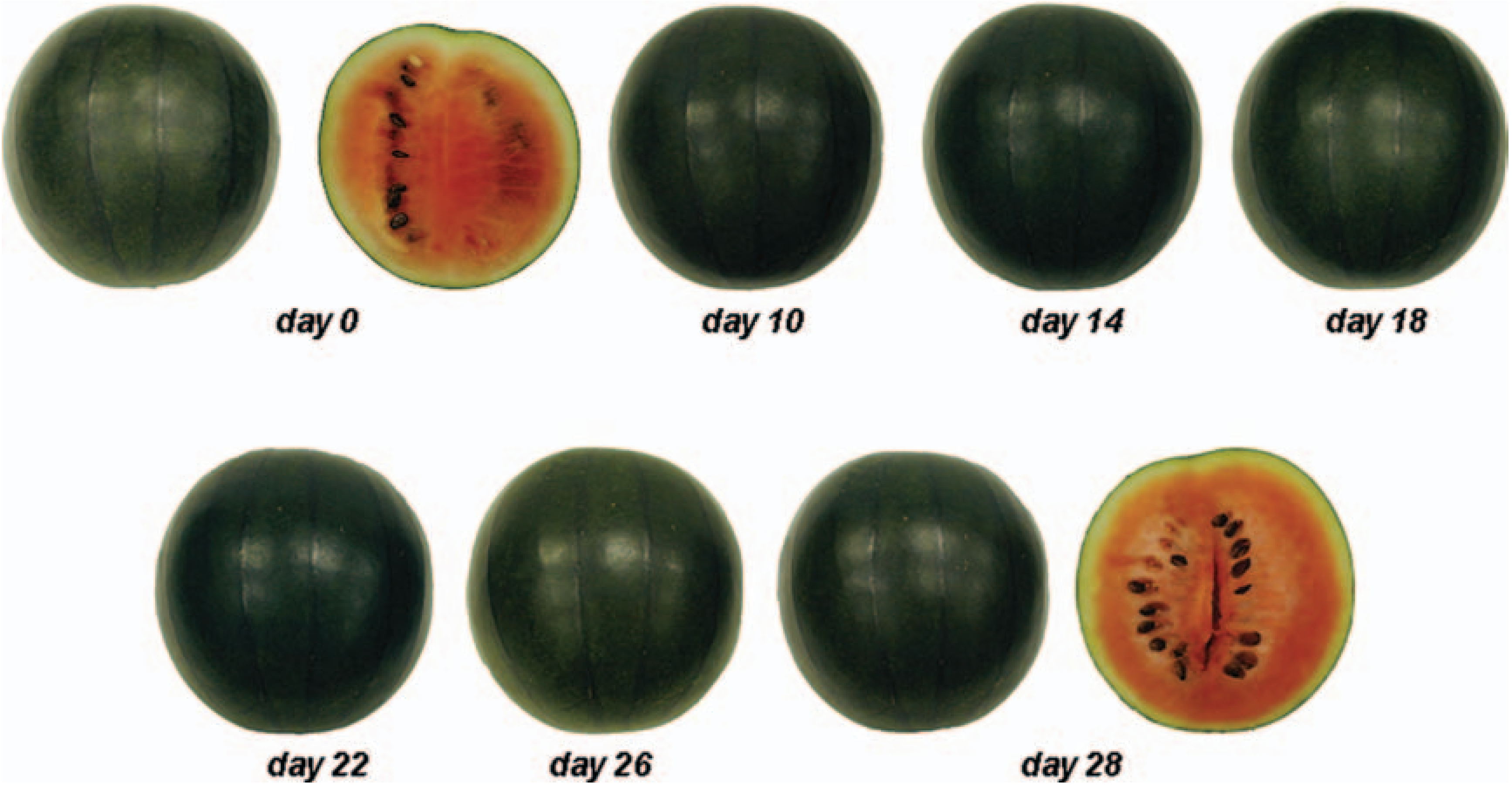

day 0
day 10
day 14
day 18
day 22
day 26
day 28

Figure 4.19. Appearance of ‘Sugar Baby’ watermelon stored for 28 days at 20°C. After 28 days the watermelon rind appears more dark-green and the internal rind and flesh appear very dry, mealy, and discolored.

YELLOW SQUASH

Scientific Name: *Cucurbita pepo* L.
Family: Cucubitaceae

Quality Characteristics

Summer squash is a warm-season crop and is usually classified based on fruit shape and color. The most common forms of summer squash are straight neck, crookneck, semi-crookneck, and zucchini squash. Zucchini is the most important summer squash cultivar and is grown worldwide year-round (McCollum 2004). Summer squash quality is based on uniform shape, tenderness of rind and internal tissues, overall firmness and a glossy skin color, and an intact well-trimmed stem portion (Boyhan et al. 1999). Smaller squashes have normally tender skin and flesh and softer seeds, and their flavor is mild and slightly sweet compared to larger squashes (Ryall and Lipton 1979).

Yellow summer squash contains about 94% water, 4% carbohydrates, 0.9% proteins, 2% fiber, 8 mg of vitamin C, 410 μg of β-carotene, and minor amounts of other vitamins per 100 g of fresh fruit (Holden et al. 1999; Marlett and Vollendroft 1993; USDA 2006).

Optimum Postharvest Handling Conditions

Pre-cooling summer squashes promptly after harvest using room air, forced-air, or hydro-cooling reduces the rate of water loss and results in extended postharvest life (McCollum 2004). Following pre-cooling, the optimum storage temperature for summer squashes is between 5 and 10°C and 85–90% humidity, depending on the cultivar and storage length. Summer squashes should not be stored for more than 10 days, as they deteriorate rapidly after harvest (Boyhan et al. 1999; Hardenburg et al. 1986; McCollum 2004). Squashes are injured when stored at low but non-freezing temperatures. Critical threshold temperatures for CI symptoms are below 5°C. Although summer squashes are shown to be chilling sensitive at temperatures below 5°C, if held for more than a day or 2, cultivars also vary in their chilling sensitivity (McCollum 2004).

Temperature Effects on Quality

Quality of yellow summer squashes is greatly affected by storage temperature. For example, squash fruits held at 0°C for 4, 8, and 12 days deteriorated rapidly upon transfer to room temperature (20–25°C and 60–75% humidity), and the rate of deterioration was proportional to the duration of holding at 0°C. The rate of quality loss in fruits held at 5°C was similar to that observed in squashes held at 0°C during 12 days of storage (Maksoad et al. 1975). Exposing yellow summer squashes to temperatures below the critical ranges (i.e., below 5°C) causes cellular breakdown and loss of membrane integrity. These injuries lead to increased membrane permeability and exudation of cellular liquid to intracellular spaces (Buta and Wang 1993; McCollum et al. 1991). If chilling exposure continues more symptoms develop, such as water-soaked appearance, discoloration, surface browning, and pitting and tissue collapse. Usually the symptoms aggravate when summer squashes are transferred to ambient temperature (Wang 1994, 1995). For example, yellow summer squashes developed surface pitting after 3–6 days at 2°C, which was progressively more severe with increasing duration of chilling. After transfer to 15 or 20°C, the surface pitting became even more extensive (Lee and Yang 1999; McCollum 1989). Compared to zucchini held for 1 day at 15°C, there was significant fluid leakage from the cortical tissue of fruit held for the same period at 5°C; however, no visible symptoms of CI were observed. After 3 days at 5°C, surface pitting was evident and leakage was detected even before the development of visual CI symptoms (Buta and Wang 1993). Likewise, symptoms of CI in zucchini squashes manifested as surface pitting on the skin, which appeared after 4 days at 5°C, aggravated with time, and affected the market quality (Wang 1994, 1995). When exposed for 14 days to 2.5°C almost all the zucchinis developed some degree of pitting, and the symptoms aggravated after transfer to 10°C (Mencarelli et al. 1983). Storage of zucchini squashes at 5°C resulted in rapid development of CI. Surface pitting started to appear after 3 days of exposure at 5°C, and after 10 days most fruit developed moderate to severe pitting (Wang et al. 1992). Sherman et al. (1985) suggested that 5°C storage of yellow straight necks and zucchinis was too low for Florida-grown summer squashes, and, in fact, after 2 days CI was evident in Florida-grown summer squashes stored at 5°C (McCollum et al. 1991). However, yellow summer squash cultivars may vary in their susceptibility to CI. Sherman et al. (1985) reported that after 22 days at 5°C 'Multipik' yellow summer squashes were severely discolored and unacceptable, whereas 'Seneca Butterbar' fruit had an acceptable appearance. 'Medallion' yellow squash was more sensitive to chilling temperatures than 'Horn of Plenty' yellow squash. After approximately 5 days at 0 or 5°C, 'Horn of Plenty' squashes developed pitting of the skin, peel discoloration, scalding, and minor signs of decay, whereas in 'Medallions' signs of CI became objectionable after 3 days at 0 or 5°C (Nunes et al. 2003).

Holding yellow summer squashes at chilling temperatures also accelerates the development of decay, particularly when squash is subsequently transferred to ambient temperature. For example, after 19 days at 5°C, summer squashes showed more than 50% decay, and within 2 days after transfer to 20–25°C decay increased to 100% (Maksoad et al. 1975). Similar levels of decay were reported for summer squashes stored at nonchilling temperatures. For example, summer squashes stored at 10°C reached 50% decay after 21 days of storage (Maksoad et al. 1975), whereas yellow summer squashes stored for 20 days at 12°C showed accelerated deterioration and were no longer marketable (Lee and Yang 1999).

Preconditioning zucchini squashes at 15°C for 2 days prior to storage at 5°C was shown to delay the onset of CI symptoms as well as reduce the severity of the symptoms. Compared to nonpreconditioned squashes that developed CI symptoms after 3 days at 5°C, in preconditioned squashes surface pitting was not noticeable until 6–8 days, and only slight pitting was observed after 16 days at 5°C (Wang et al. 1992).

Rind injuries were observed in summer squashes held at nonchilling temperatures. Development of warts on the skin of yellow squashes may occur later after harvest, when squashes are stored at nonchilling temperatures (McCollum 1989). Development of warts in the rind of summer squashes after several days in storage was first attributed to chilling damage. However, microscopic analysis of the injuries showed that the cause was probably due to heat injury caused by higher temperatures during growth rather than chilling damage (McCollum 1989). In summer squashes stored at 10, 15, and 20°C, development of warts was marked and rendered the fruit unacceptable for sale (Nunes et al. 2003).

L* value of yellow squashes decreased, regardless of the storage temperature, but the decrease was more evident in fruits stored at 15 and 20°C. For 'Medallion' squashes stored at 20°C, the L* value showed a significant decrease after 8 days, meaning that the color of the squashes turned from a bright yellow to a darker yellow (lower L* value) (Nunes et al. 2003). Smittle et al. (1980) also observed increased yellowing in squashes after 3 days of storage at 15°C. Hue of yellow squashes also decreased during storage regardless of the temperature. But again, changes in color were more evident in fruits stored at higher temperatures. Decrease in hue value from about 90–80° represents changes in the superficial color from a yellow to an orange-yellow, exactly as the visual color changes observed during storage of yellow summer squashes. Chroma of 'Medallion' yellow squashes followed the same pattern as hue value and decreased, regardless of the storage temperature. The yellow color of squash was less vivid after storage than at harvest, and squashes stored at 15 and 20°C showed a greater decrease in chroma compared to those stored at lower temperatures (Nunes et al. 2003). In addition to darkening of the typical yellow color of squashes that occurs, bruised areas on the skin of yellow squashes may develop some discoloration or browning during storage. For example, Smittle et al. (1980) reported that summer squashes developed a slight browning on bruised areas after 9 days of storage at 15°C, whereas Lorenz (1951) reported that bruised skin of squashes turned brown after 2 days at 15°C.

Firmness of 'Medallion' yellow squashes decreased during storage, regardless of the storage temperature. However, 'Horn of Plenty' squashes stored at chilling temperatures (0 and 5°C) showed a greater decrease in firmness when compared to squashes stored at nonchilling temperature (10, 15, and 20°C). Firmness of 'Medallion' and 'Horn of Plenty' yellow squashes stored at 0°C was comparable to firmness of squashes stored at 20°C, and after approximately 6 days, firmness of yellow squashes stored at either 0 or 20°C was no longer acceptable (Nunes et al. 2003). Decreased firmness in squashes stored at lower temperatures might have resulted from loss of membrane integrity and cell damage caused by chilling. Injury of the cells due to chilling is often accompanied by water exudation and loss of turgidity of the tissues, similar to that observed at high storage temperatures due to water loss (Marangoni et al. 1996).

According to the literature, the first signs of shriveling in yellow crookneck squashes are noted when weight loss reaches 10–58%, depending on the cultivar. Deterioration in commercial appearance accompanies moderate shriveling symptoms, which are noted when weight loss reaches 9–24% (Hruschka 1977). 'Horn of Plenty' yellow squashes showed a maximum weight loss of about 11% after 12 days at 10°C, with minimal shriveling, whereas weight loss of 'Medallion' yellow squashes reached a maximum of approximately 9, 16, and 17% after 14 days at 10, 15, and 20°C, respectively, and, consequently, moderate to unacceptable signs of shriveling were evident (Nunes et al. 2003). Sherman et al. (1987) showed that weight loss during storage under the same temperature and relative humidity conditions depends on cultivar characteristics. After 14 days at 5°C, weight loss of different squash cultivars may vary from a maximum weight loss of 15% to a minimum of 3%, depending on the cultivar.

At the time of harvest the pH of 'Horn of Plenty' squashes was slightly lower than that of 'Medallions,' approximately 6.1 and 6.2, respectively (Nunes and Emond 2002). During storage there was a slight increase in pH, but there was no significant difference between the pH of squashes stored at

0 and 5°C. At the time of harvest the acidity of squashes was similar, 0.06% and 0.08% of malic acid for 'Horn of Plenty' and 'Medallion' squashes, respectively (Nunes and Emond 2002). Acidity of squashes expressed in terms of dry weight significantly increased during storage, regardless of the temperature. However, increase in acidity was more marked in 'Medallion' squashes stored at 10, 15, and 20°C when compared to 'Horn of Plenty.' At 0 and 5°C, squashes showed approximately the same rate of acidity increase (Nunes and Emond 2002). The initial soluble solids content of the squashes was different between cultivars. The soluble solids content of 'Horn of Plenty' squashes was approximately 4.8% at the time of harvest, compared to 4.5% in 'Medallion' squashes. Soluble solids content decreased during storage, particularly in squashes stored at 15 and 20°C. However, there was a significant increase in the soluble solids content of squashes stored at 10°C compared to those stored at 0 or 5°C. In an earlier study, Lorenz (1951) reported no consistent changes in sugars or in total solids during storage of yellow summer squashes at 0°C. However, storage at 10, 15.5, and 21°C resulted in a large initial decrease in starch and alcohol-insoluble material, and the decrease was proportional to the rise in temperature. The slight increase in soluble solids content observed in summer squashes stored at 10°C might have resulted from the conversion of starch into sugars as suggested earlier by Lorenz (1951). Starch content in squashes stored at 10, 20, 25, and 30°C decreased throughout storage, regardless of the temperature, whereas total sugar content increased, reaching a maximum, and then decreased. Best eating quality of squash was achieved when starch content was equal to the total sugar content (Nagao et al. 1991).

At the time of harvest, ascorbic acid content of 'Horn of Plenty' squashes from the first harvest was significantly lower than that of 'Medallion' squashes, 35.2 mg per 100 g and 51.5 mg per 100 g fruit fresh weight, respectively. The ascorbic acid content of the squashes decreased significantly during storage, and a sharp decrease was observed after 2 days of storage, regardless of the temperature. Squashes stored at 5 and 20°C showed the highest ascorbic acid reduction during storage compared to storage at 0, 10, or 15°C. However, after 7 days the ascorbic acid content of squashes stored at 5°C was no different than that of squashes stored at 10°C (Nunes and Emond 2002). Wang (1996) also reported a decrease in the ascorbic acid content of zucchini squashes after storage for 2 days at 5°C, which continued to decline during further storage. Decrease in the ascorbic acid content of squashes stored at 5°C might have resulted from CI that affected the squashes stored either at 0 or 5°C. In fact, after approximately 3 days, 'Medallion' squashes stored at 0 or 5°C showed moderate signs of chilling injury (Nunes and Emond 2002). Chilling injury may have resulted in damage to the cell walls, and consequently in release of the enzyme ascorbate oxidase, which oxidizes the ascorbic acid into inactive forms (Klein 1987; Loewus and Loewus 1987; Nobile and Woodhill 1981).

Time and Temperature Effects on the Visual Quality of 'Medallion' Yellow Squashes

'Medallion' yellow squashes shown in Figures 4.20–4.27 were harvested at the immature tender stage and with glossy appearance from a commercial operation in Homestead, Florida, during the winter season (i.e., February to March). Promptly after harvest, fresh yellow squashes were stored at five different temperatures (0.5 ± 0.3°C, 5.0 ± 0.2°C, 9.4 ± 0.4°C, 14.40 ± 0.4°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Visual quality of 'Medallion' yellow summer squashes changes during storage, but the type, severity, and rate of changes depend on the storage time and temperature. Major visual changes during storage of yellow summer squashes at temperatures below 5°C are mainly related to CI. In yellow squashes stored at temperatures above 5°C, darkening of the color, brown discoloration, and decay are the major visual changes observed. In addition, when summer squashes are stored at nonchilling temperatures, rind injury (i.e., warts) may also develop due to preharvest exposure to extreme field heat.

'Medallion' yellow summer squashes stored continuously at 0°C maintain acceptable quality during 6 days. After 6 days, the squashes show some spots of brown discoloration on the rind, which increases slightly after 8 days (Figure 4.20). However, squashes exposed for 4 days at 0°C and then transferred to 20°C for 2 additional days show pitting on the rind, and after a 6-day exposure severe pitting, scalding, and slight decay develop on the squashes upon transfer to 20°C for 2 additional days (Figure 4.22).

Squashes stored at 5°C maintain acceptable visual quality during 6 days. After approximately 6 days, surface pitting and brown discoloration become evident and aggravate as storage progresses (Figure 4.21). Yet, upon transfer of squashes to 20°C for 2 additional days, after storage for 10 days at 5°C, pitting does not aggravate significantly and reaches about the same level of that in fruit stored for 4 days at 0°C before transfer to higher temperature (Figure 4.22).

'Medallion' squashes stored at 10°C maintain acceptable visual appearance up to 14 days. After 6–8 days the color of the squashes changed from a light yellow to a darker orangish-yellow, yet the visual quality of the squashes is still acceptable (Figure 4.23). However, after approximately 8 days squash firmness decreases and the fruit becomes softer.

As temperature increases from 10 to 15°C, yellow color of squashes changes more rapidly from a bright light yellow at harvest to a darker orangish-yellow during storage. Squashes stored at 15°C maintain acceptable visual quality during 12–14 days of storage, but after 14 days the color of squashes appears much darker than initially (Figure 4.24). After 6–8 days the squash is already very soft and the neck bends easily.

'Medallion' squash stored at 20°C maintains acceptable visual quality for 8–12 days, yet the color changes from a light yellow to a dull dark orangish-yellow after 14 days (Figure 4.25). After 6 days squash firmness decreases and the fruit becomes softer and spongy, and the neck bends easily. At this temperature loss of moisture is in general very rapid, and after 5 days squash shows dryness of the internal flesh, particularly in the neck area (Figure 4.26). Browning on intentionally abraded surfaces and decay also develop after 8 and 14 days at 20°C, respectively (Figure 4.26).

Preharvest factors usually related to extreme high temperatures during development of yellow summer squashes in the field also affect the visual quality of the squashes during postharvest storage at temperatures higher than 5°C. After 8 days at 10°C, ‘Medallion’ yellow summer squashes develop round sunken and leaky lesions on the rind (i.e., warts). Squashes stored at 15 or 20°C also develop the same type of lesion after 10 or 4 days, respectively, and in severe cases the fruit is completely covered with warts (Figure 4.27).

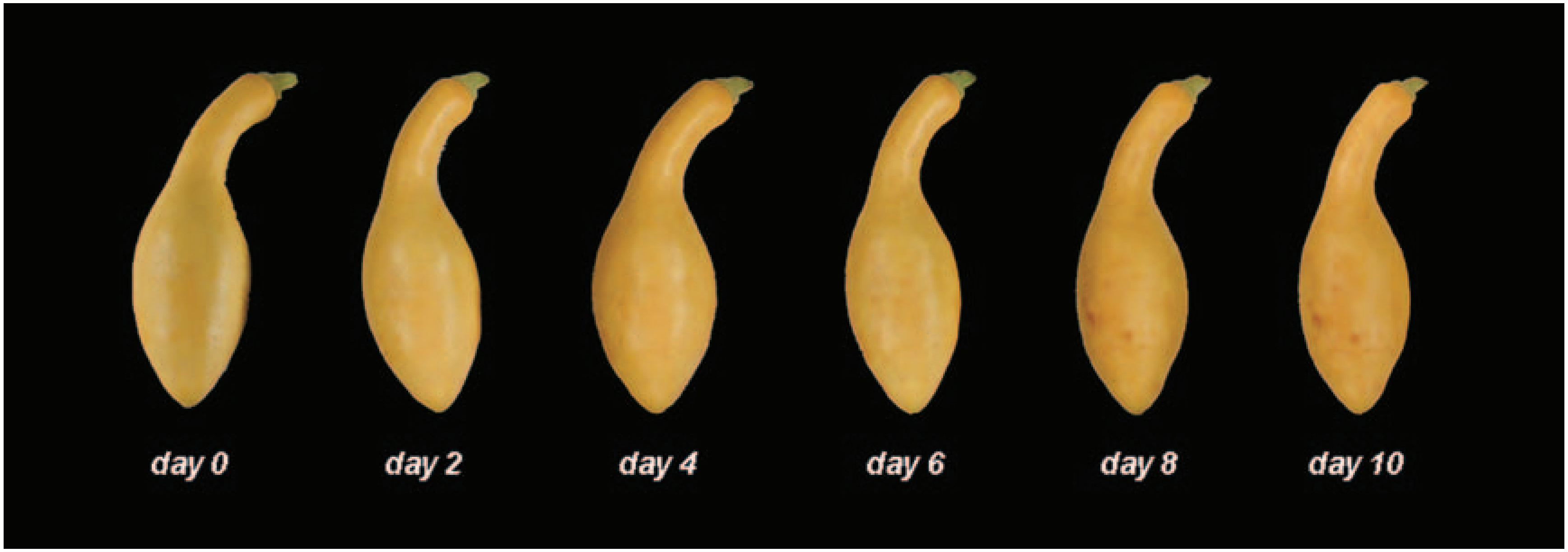

day 0
day 2
day 4
day 6
day 8
day 10

Figure 4.20. Appearance of ‘Medallion’ yellow summer squash stored for 10 days at 0°C. After 6 days, squash shows some spots of brown discoloration on the rind.

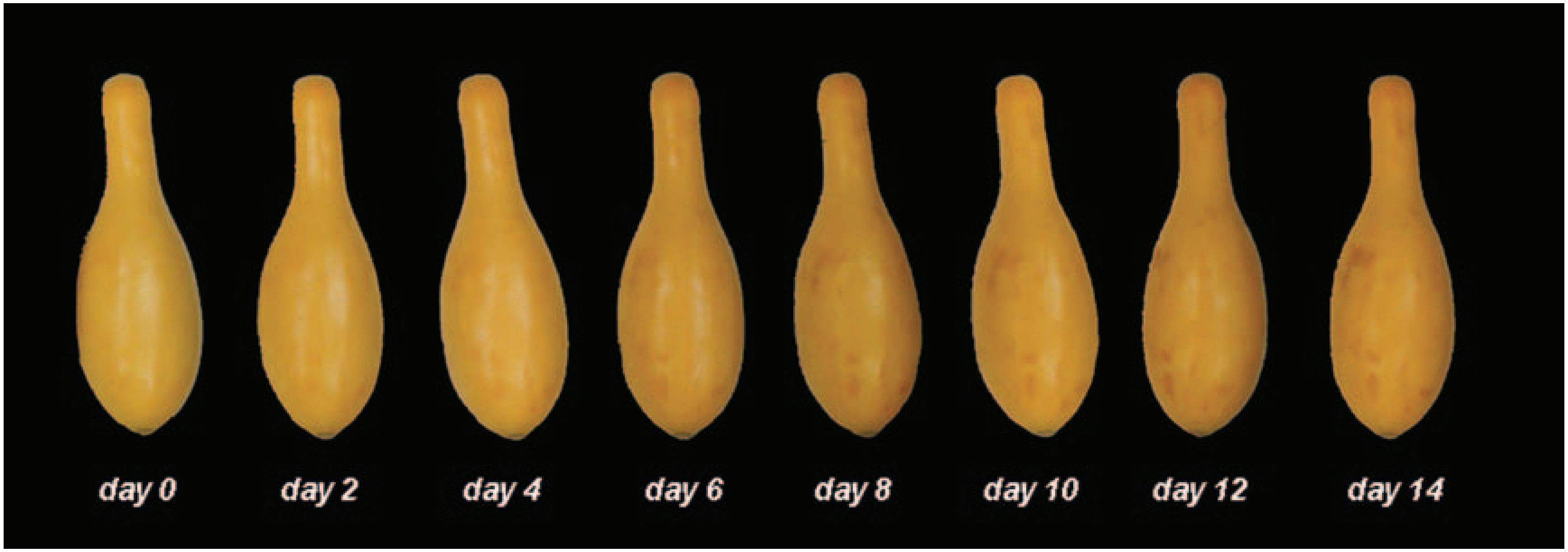

day 0
day 2
day 4
day 6
day 8
day 10
day 12
day 14

Figure 4.21. Appearance of 'Medallion' yellow summer squash stored for 14 days at 5°C. After approximately 6 days surface pitting and brown discoloration develop and after 14 days symptoms appear more severe.

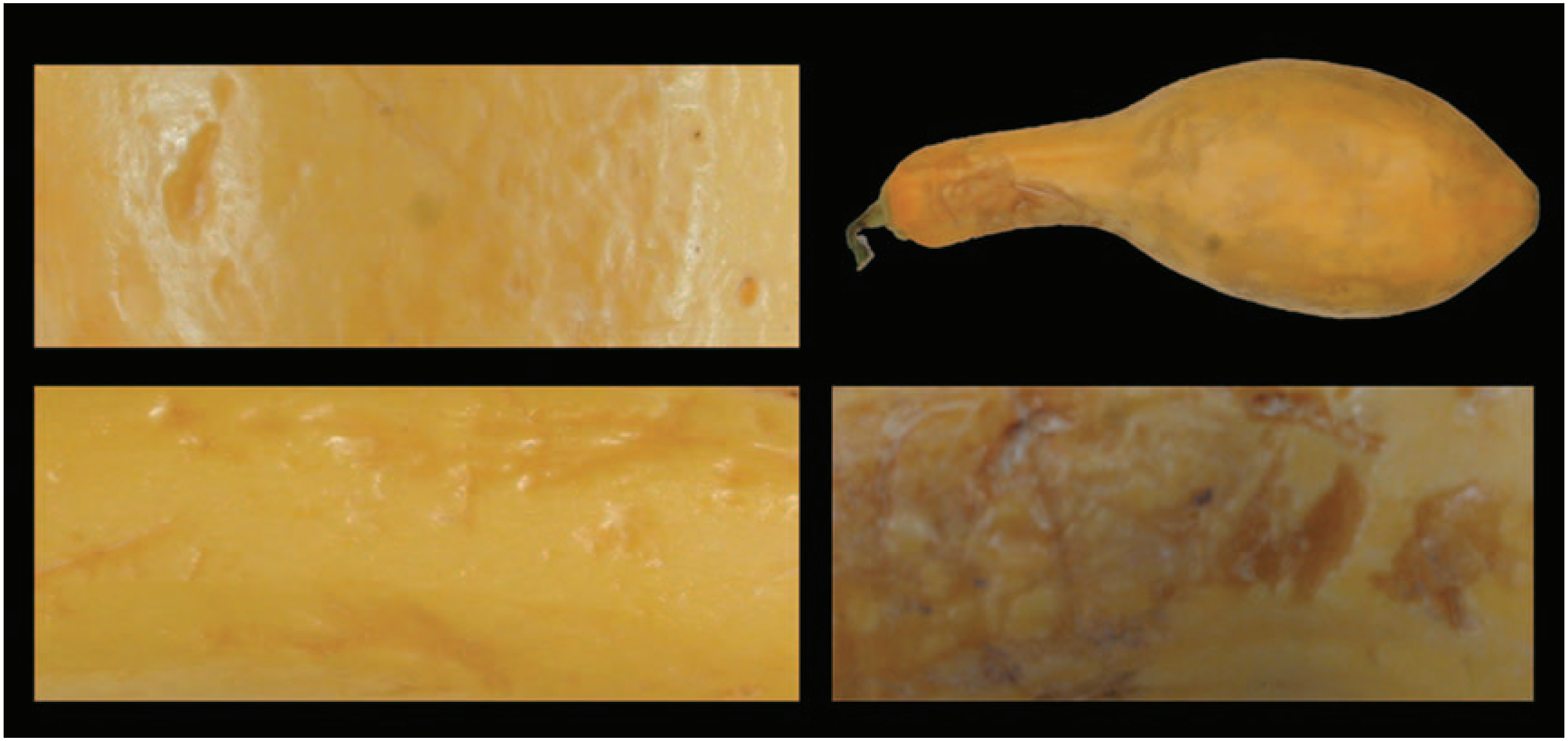
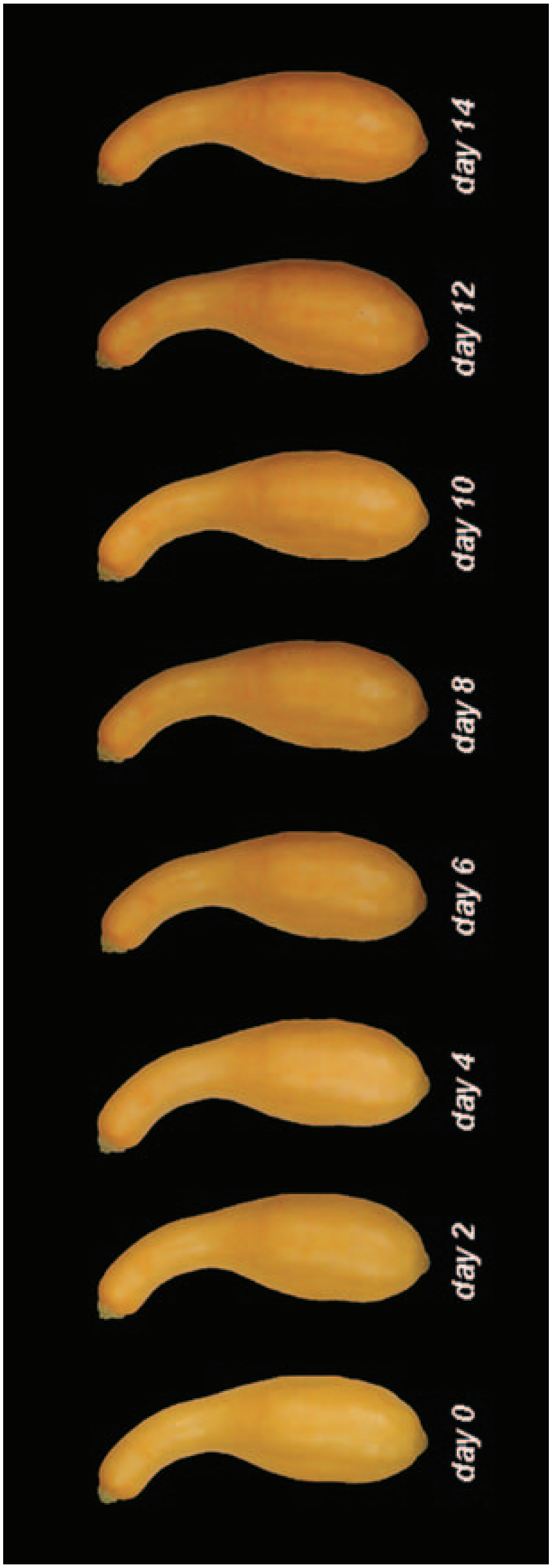


Figure 4.22. Chilling injury in 'Medallion' summer squash after transfer from 0 and 5°C to 20°C for 2 additional days. Squash stored for 4 days at 0°C shows pitting of the rind (top left). After 6 days at 0°C pitting, discoloration, and scalding of the skin increase in severity, and a slight decay development is also noticeable (right). After 10 days at 5°C pitting develops on the rind of the squash upon transfer for 2 additional days at 20°C (bottom left).


day 0
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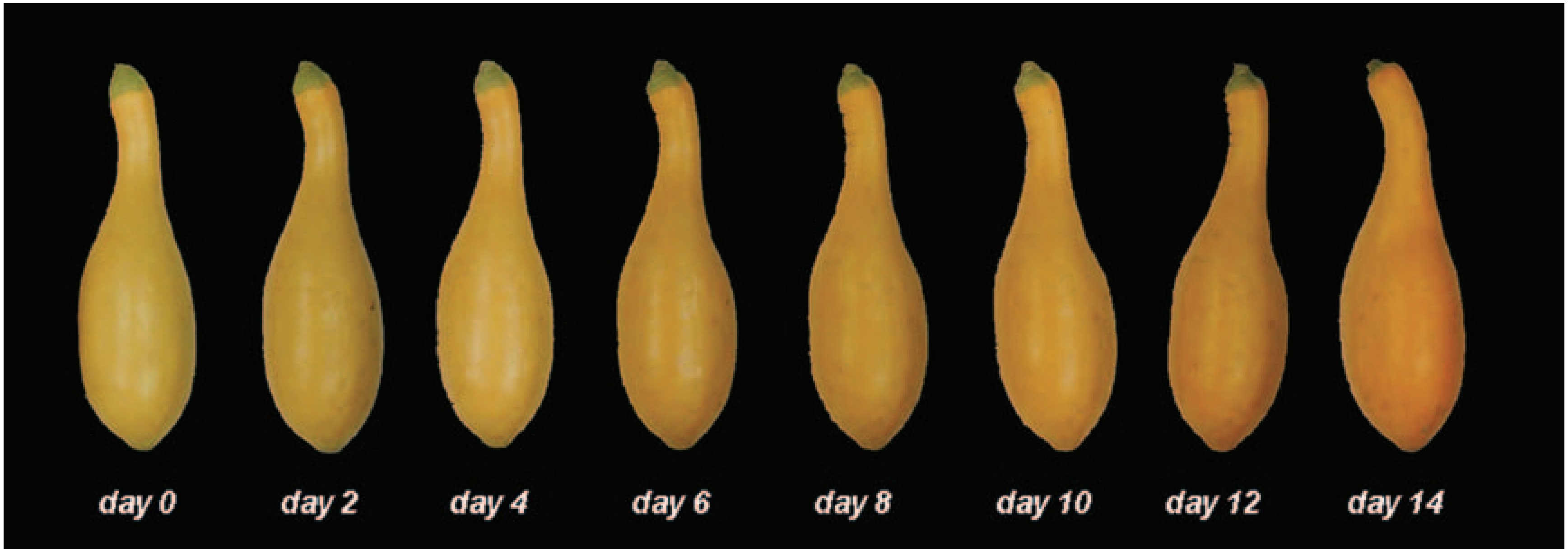
day 10
day 12
day 14

Figure 4.23. Appearance of 'Medallion' yellow summer squash stored for 14 days at 10°C. After 6–8 days the color of the squash changes from a light yellow to a darker orangish-yellow.


day 0
day 2
day 4
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day 8
day 10
day 12
day 14

Figure 4.24. Appearance of ‘Medallion’ yellow summer squash stored for 14 days at 15°C. Squash maintains acceptable visual quality during 12–14 days of storage, but after 14 days the color of squash appears much darker than initially.

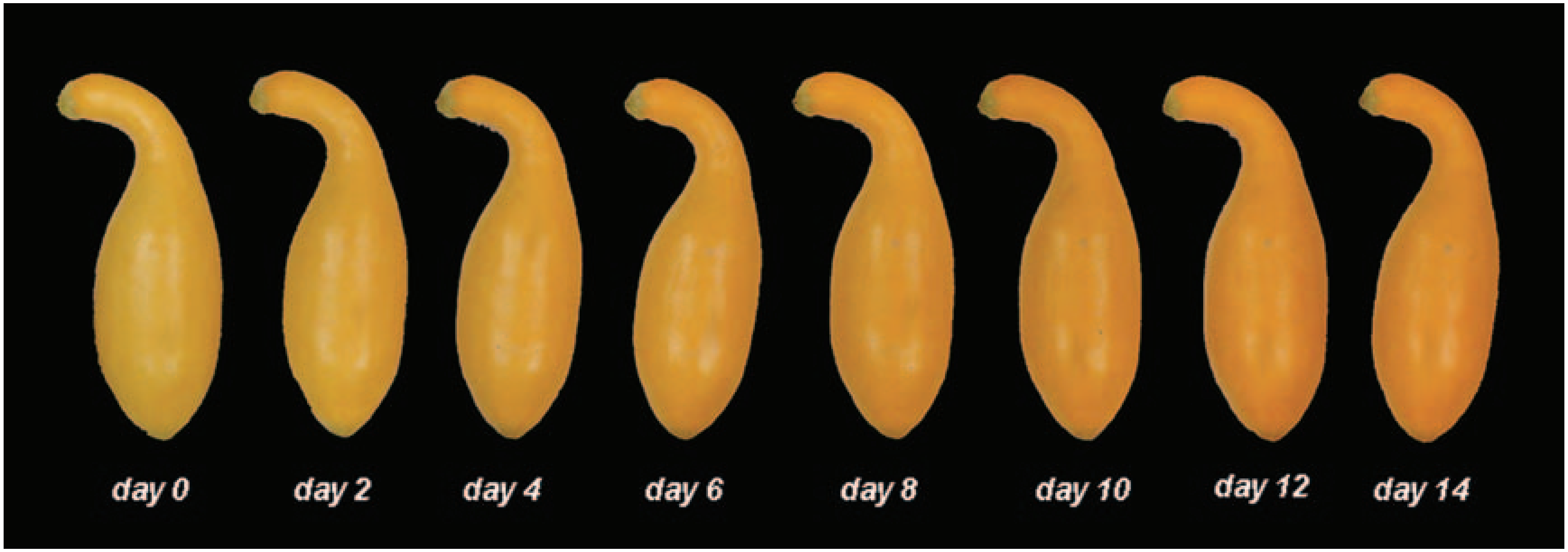
day 0
day 2
day 4
day 6
day 8
day 10
day 12
day 14

Figure 4.25. Appearance of 'Medallion' yellow summer squash stored for 14 days at 20°C. Squash maintains acceptable visual quality for 8–12 days, yet the color changes from a light yellow to a dull dark orangish-yellow after 14 days.

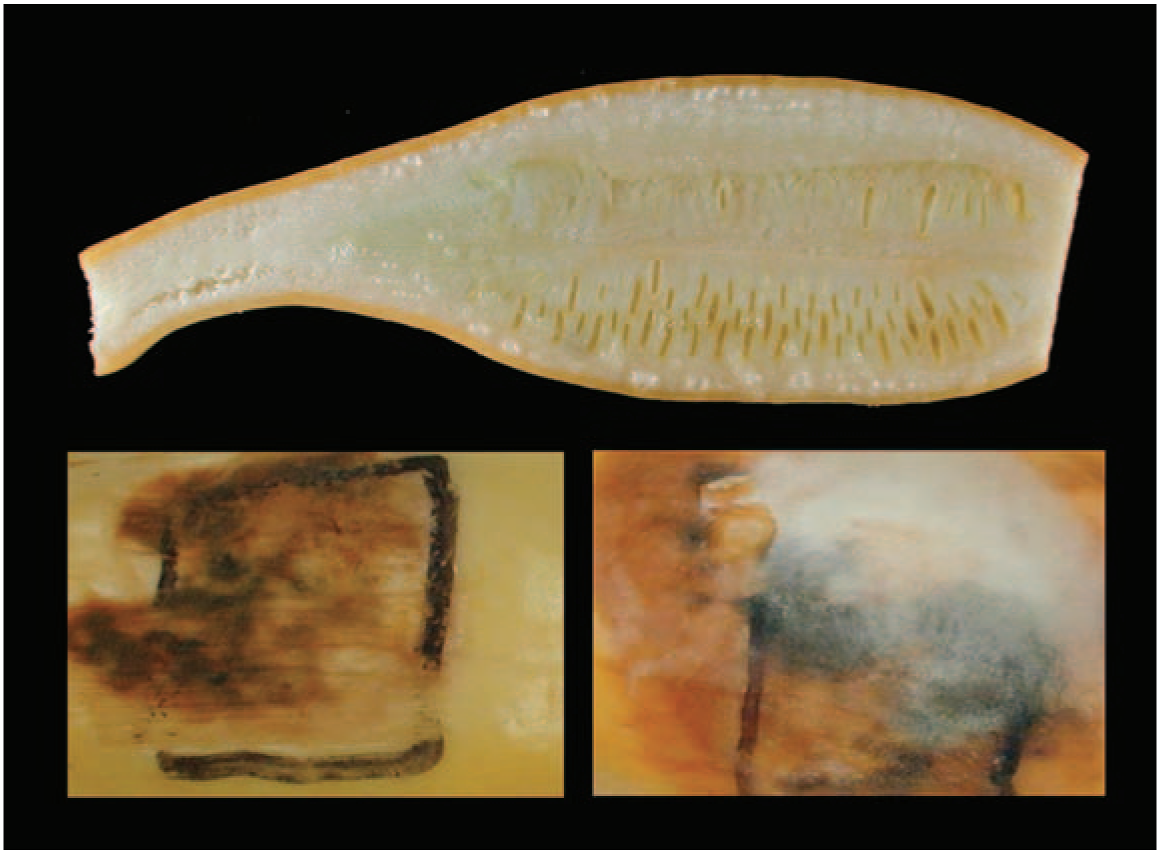

Figure 4.26. High-temperature disorders in 'Medallion' yellow summer squash stored at 20°C. Dryness of the neck in squash after 5 days (top), browning on intentional abraded area after 8 days (bottom left), and browning and decay on intentionally abraded area after 14 days (bottom right).

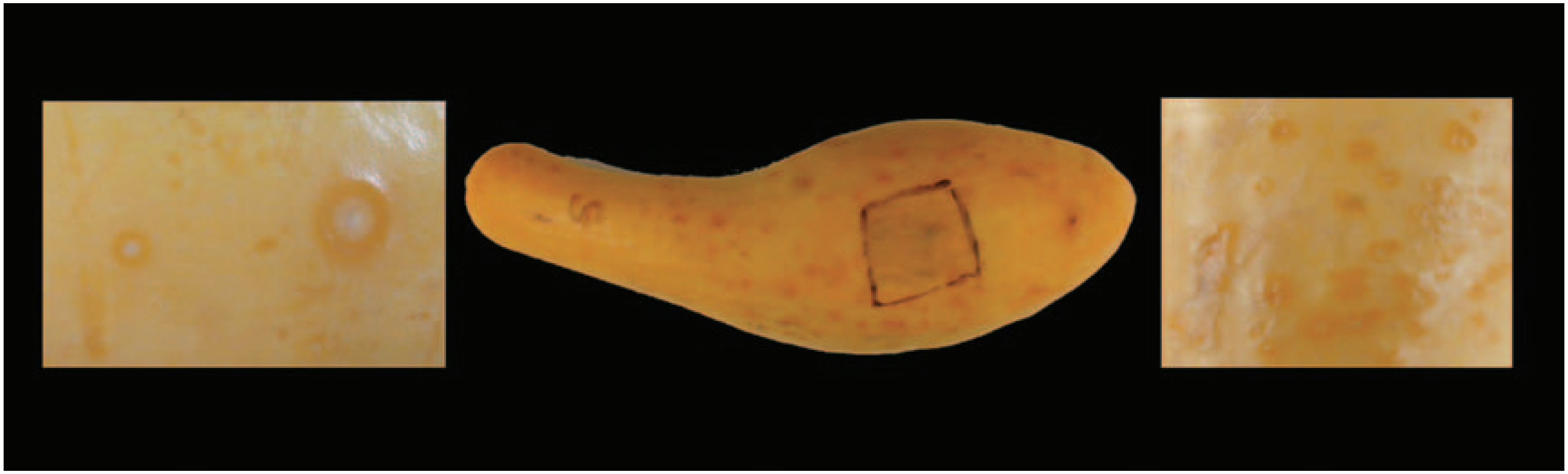

Figure 4.27. Pre-harvest-related disorders in ‘Medallion’ yellow summer squash stored at 10, 15, or 20°C. Warts develop on the rind of the squash after 8 days at 10°C (left), after 10 days at 15°C (middle), and after 4 days at 20°C (right).

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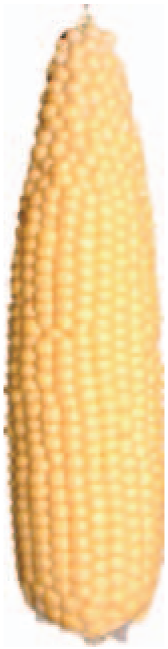

CHAPTER 5

SOLANACEOUS AND OTHER FRUIT VEGETABLES

Tomato
Cape Gooseberry
Green Bell Pepper
Eggplant
Sweetcorn
Bibliography

Color Atlas of Postharvest Quality of Fruits and Vegetables Maria Cecilia do Nascimento Nunes

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TOMATO

Scientific Name: *Solanum lycopersicum* L.
Family: Solanaceae

Quality Characteristics

Tomato fruit is one of the horticultural crops most consumed worldwide. Nowadays we can find in the fresh market a large variety of tomatoes with different shapes, colors, and sizes. The round red-fleshed tomato types are still the most popular, but the yellow and orange round types, as well as cluster (i.e., ripened on-the-vine and sold in a bunch with the stem still attached), plum (roma-type tomato), and the small-sized red types such as cherry, grape, and mini-pear are also available in the fresh market (Sargent and Moretti 2004).

The quality of fresh tomato fruit is determined by various attributes such as appearance, firmness, flavor, and nutritional value. Because consumers purchase tomatoes largely based on appearance, fruit should be well formed, have a uniform orange-red to deep red color with no green shoulders, and have a smooth appearance (Kader et al. 1978). Color is one of the most important quality factors that affect tomato appearance and is determined by skin and flesh pigmentation (Brandt et al. 2006). As tomatoes ripen, the color changes from green in immature fruit to deep dark red in fully mature fruit. Tomato color is greatly correlated with lycopene content, and as the fruit develops from the mature green stage to the red stage, lycopene concentration increases significantly (Brandt et al. 2006; Dumas et al. 2003; Helyes et al. 2006).

The increase in a* value measured by a chromameter was shown to be directly associated with lycopene synthesis, whereas a*/b* ratio has been reported to be a good indicator of lycopene content and, therefore, could be used to characterize fresh tomato ripeness stage (Arias et al. 2000; Helyes et al. 2006). At the breaker stage, a*/b* value was either null or negative (prevalence of green color) and carotenoid content was insignificant, whereas in vine-ripened tomatoes, lycopene and β-carotene concentrations progressively increased (Giovanelli et al. 1999). However, it has been suggested that color measurements of tomato varieties do not satisfactorily quantify the carotenoid content, particularly when ripening reaches the red stage (Leonardi et al. 2000). Almost half of the lycopene content of tomatoes is synthesized and accumulated during the deep red stage. Lycopene begins to accumulate after the breaker stage and, at the ripe-red stage, lycopene comprises 95% of all colored carotenoids and 73% of the total carotenoids (Dumas et al. 2003). In cluster and cherry tomatoes, lycopene represented 79–85% of the total carotenoids, respectively (Leonardi et al. 2000). However, β-carotene synthesis ceased after tomato color had changed from orange to red (Giovanelli et al. 1999).

Tomato firmness is also an important quality decisive factor because it is associated with good eating quality and longer postharvest life. As tomatoes ripen firmness decreases, and ripe fruit are much softer than mature-green fruit (Wann 1996). A good eating quality tomato should be firm and not easily deformed because of softening associated with overripeness.

Tomato eating quality is an important factor that contributes to consumer acceptability, in addition to color and firmness, measurements of acidity, total soluble solids content, and sugar-to-acid ratio, which are also used to select for desirable sweet and sour flavor attributes in tomato fruit (Baldwin et al. 1998). As tomatoes ripen, changes in fruit composition related to the normal ripening process occur. Tomato fruit ripened on the plant has higher total solids, soluble solids, and reducing sugars contents than breaker stage fruit or those ripened off the plant (Betancourt et al. 1977; Kader et al. 1977). Although the sugar-to-acid ratio is usually lower in tomatoes harvested at the mature-green stage, it increases in fruit harvested at the table-ripe stage (Watada and Aulenbach 1979). Fruit harvested green or breaker had about 10–15% less reducing sugars than that harvested at the table-ripe, dark pink, or light pink stages of color development (Kader et al. 1977). Furthermore, fruit harvested at the table-ripe stage has a higher fruity-floral aroma, is sweeter, and is less sour compared with that harvested at the mature-green or light pink stage (Kader et al. 1977, 1978; Watada and Aulenbach 1979). Tomatoes harvested at earlier stages of ripeness and allowed to ripen at 20°C were evaluated as being less sweet, more sour, less "tomato-like," and having more off-flavor than those harvested at the table-ripe stage (Kader et al. 1977). Therefore, tomatoes allowed to ripen on the vine typically have higher soluble solids content, lower acidity, and higher sugar-to-acid ratio but are less firm compared with tomatoes harvested when they are less ripe. In addition, tomato volatiles increase as tomato fruit ripens, and volatile formation is closely related to fruit coloration (Lin and Block 1998).

Ascorbic acid content also tends to increase as the fruit matures and is usually higher in vine-ripe tomatoes than in mature-green tomatoes (Dumas et al. 2003; Scott and Kramer 1949; Slimestad and Verheul 2005). Tomato fruit harvested at the breaker stage and ripened postharvest at 20°C contained only 43.6–62.9% of its potential ascorbic acid content if ripened on the plant to the table-ripe stage. Therefore, tomatoes ripened on the plant accumulate more ascorbic acid than fruit ripened off the plant (Betancourt et al. 1977).

Table-ripe (red) tomatoes contain on average 94% water, 5% carbohydrates, 0.9% proteins, and 1% fiber, 19 mg of vitamin C, and 623 IU of vitamin A per 100 g of fresh fruit (Marlett and Vollendorf 1993; USDA 2006). However, depending on the type of tomato cultivar, ascorbic acid content can range from 14.6 to 21.7 mg per 100 g fresh weight of tomato fruit (Abushita et al. 2000).

Optimum Postharvest Handling Conditions

Prompt cooling of freshly harvested tomatoes to 15–20°C, when field temperatures are higher than 30°C, may contribute to reduced disease incidence and extended postharvest life (Bartz et al. 1991). In addition, weight loss and fruit softening are reduced and ripening delayed during subsequent storage of pre-cooled green tomatoes compared with non-pre-cooled fruit (Kaynas and Sivritepe 1995).

Subsequent to pre-cooling, optimum storage temperature depends on the maturity or ripeness of the tomato fruit at harvest. Immature- and mature-green tomatoes are more sensitive to chilling temperatures than pink or red tomatoes are. If held for longer than 2 weeks below 10°C or for longer than 6–8 days at 5°C, they may develop chilling injury (CI). Consequences of CI are failure to ripen and develop full color and flavor, irregular (blotchy) color development, premature softening, surface pitting, browning of the seeds, and increased decay. Consequently, mature-green tomatoes can be stored up to 14 days between 12.5 and 15°C without major decreases in flavor or color development, whereas immature-green fruit would be injured by that time-temperature combination (Hardenburg et al. 1986). Similarly, to guarantee a normal postharvest life during retailing, light red tomatoes should be stored for no longer than 10 days between 10 and 12.5°C. A storage temperature of 10–13°C has been recommended for pink-red to firm-red greenhouse-grown tomatoes (Alban 1961). It has been shown that firm ripe tomatoes can be stored at temperatures between 7 and 10°C for 3–5 days without reduction in flavor and aroma quality (Sargent and Moretti 2004).

Temperatures recommended for tomato ripening are between 19 and 21°C for standard ripening, and for slow ripening between 14 and 16°C. Optimum development of red color occurs between 19 and 21°C, whereas lower or higher temperatures within the 13–25°C range result in slower color development or more orange fruit, respectively. Higher temperatures (especially greater than 30°C) inhibit red color development. A high relative humidity (90–95%) during postharvest handling is essential to avoid loss of moisture and shriveled appearance of the fruit (Sargent and Moretti 2004; Suslow and Cantwell 2006b).

Temperature Effects on Quality

Postharvest handling temperature has a major effect on tomato quality. In general, the rate of ripening and changes in the color of tomatoes increase as storage temperature increases. Color development in tomato as measured by a chromameter is characterized by lower L* value (lightness) readings, a change from negative to positive a* values, decrease in hue angle, and increase in chroma (Shewfelt et al. 1988). McDonald et al. (1999) reported that tomatoes ripened at 20°C had higher a*/b* values compared with tomatoes stored at 2°C, meaning that nonchilled fruit had a more intense red color than chilled fruit. Tomatoes stored for 1 week at 2°C developed normal color and no fungal rots after transfer to 20°C. However, after 11 days at 2°C, decay started to be evident and color development was impaired. After 3 weeks at 2°C the tomatoes no longer developed red color (Lurie and Sabehat 1997). The L* value of 'Trust' tomatoes stored at 0 or 5°C did not change significantly during storage when compared to the L* value of tomatoes stored at 10, 15, or 20°C, which decreased during storage. This was most likely due to the fact that tomatoes stored at chilling temperatures were not able to ripen normally, whereas after 4 days at 10, 15, or 20°C, 'Trust' tomatoes were completely red (Proulx et al. 2001). Likewise, storage of mature-green 'Caruso' tomatoes for 15 days at 5°C induced slight symptoms of CI, such as accelerated fruit softening and nonuniform red color development after transfer to 22°C. Although the green color of 'Caruso' tomatoes harvested at the mature-green stage and stored for 30 days at 5°C remained unchanged, the fruit became light green and yellow, but no red color developed after transfer to 22°C (Jackman et al. 1992).

In tomato fruit stored at 20°C, a gradual decrease in L* value was observed from 50.8 at the turning stage to 42.7 at the red stage, indicating darkening of the tomato skin (Nussinovitch et al. 1996). Auerswald et al. (1999) also reported a decrease in L* value of tomatoes after storage at 20°C for 7 days. Tomatoes harvested mature-green to full ripe and then stored at 20°C showed a linear increase in a*/b* values during 12 days of storage. (Giovanelli et al. 1999). Hue of 'Trust' tomatoes stored at 10, 15, or 20°C decreased during storage but remained stable in tomatoes stored at lower temperatures. The decrease in hue value from about 74 to 45 degrees in those tomatoes corresponded to changes in the superficial color from reddish-orange to dark red, exactly like the visual color changes observed during storage. Chroma of 'Trust' tomato fruit increased slightly during storage regardless of the temperature (Proulx et al. 2001). Green tomatoes stored at 37°C for 12 days developed a yellowish color, evidenced by increases in L*, b*, and chroma values, and decreases in a* value and hue. Yellowing of green tomatoes during storage under elevated abuse temperatures results from degradation of chlorophyll and incapacity to synthesize lycopene (Gnanasekharan et al. 1992).

Firmness of ‘Trust’ tomatoes decreased during storage, particularly in fruit stored at 0, 15, or 20°C (Proulx et al. 2001). After 7 days, tomatoes stored at 20°C were softer, and the fruit flesh was juicier and pulpier, whereas the epidermis was tougher (Auerswald et al. 1999). Softening in ‘Trust’ tomato fruit attained objectionable levels after approximately 11–12 days at 0°C, after 9–10 days at 15°C, and after 8 days at 20°C. Firmness of tomatoes stored at 5 or 10°C never reached objectionable levels during 14 days of storage. Firmness of ‘Trust’ tomatoes stored at 0°C declined and was comparable to that of tomatoes stored at high temperatures, most likely due to CI that developed in fruit stored at 0°C (Proulx et al. 2001). Changes in skin strength (i.e., increase in skin toughness) and premature softness are symptoms observed in tomatoes exposed to chilling temperatures, owing to loss of cell turgor arising from chilling-associated membrane dysfunction (Jackman et al. 1992; Nussinovitch et al. 1996).

Symptoms of CI in ‘Sunny’ green tomatoes occurred when the fruit was stored at or below 7.5°C, with delayed ripening occurring in fruit stored for more than 5 days at this temperature. Exposure to temperatures below 7.5°C for longer periods resulted in reduced marketable life, dull color, flaccidity, and delayed, uneven, and nonuniform ripening (Chomchalow et al. 2002). Storage of green tomatoes at 2.5°C for only 3 days resulted in uneven ripening and development of decay (Chomchalow et al. 2002). In pink ‘Trust’ tomatoes stored at 0 or 5°C, symptoms of CI became evident after approximately 4–8 days of storage and progressed to attain a maximum acceptable level after 14 days (Proulx et al. 2001). Although symptoms continued to worsen in tomatoes stored at 0°C, tomatoes stored at 5°C did not show major CI symptoms after 14 days. For tomatoes stored at 0°C, the symptoms of CI consisted of irregular coloration and development of orange rather than red pigments, pitting, and water-soaking after 12–14 days (Proulx et al. 2001). Jackman et al. (1988) observed that tomatoes stored below 7–10°C often develop CI symptoms such as enhanced microbial spoilage, pitting due to collapse of the cells beneath the skin, softening, and poor color development. CI in mature-green tomatoes stored for 7 days at 2°C increased in the subsequent 10 days at 20°C, until approximately 16% of the fruit showed pitting. After 14 and 21 days at the same temperature, CI increased, and approximately 55 and 71% of the fruit was affected (Nussinovitch et al. 1996).

Firm ripe tomatoes stored at 0 or 3°C for 15 days deteriorated rapidly (often in 24 hours) when transferred to 21°C. After 25 days, ripe tomatoes held at 3°C became soft, and many fruits had water-soaked appearance and very poor quality (Parsons et al. 1960). Increased electrolyte leakage was observed after transfer to 20°C in tomatoes harvested at the mature-green stage and stored for 2, 7, or 15 days at 5°C, before visual symptoms of CI were apparent (King and Ludford 1983).

Intermittent warming (Artés and Escriche 1994; Artés et al. 1998) and pre-storage heat treatments (Lurie and Sabehat 1997; McDonald et al. 1999; Soto-Zamora et al. 2005a, 2005b) have been applied successfully to tomatoes before exposure to chilling temperatures to prevent development of CI and to enhance color, taste, and fruit texture. For example, intermittent warming during four cycles of 6 days at 9°C and 1 day at 20°C prevented the development of pitting in tomato fruit compared with continuous storage at 9°C (Artés and Escriche 1994). Compared with tomatoes stored continuously at 9°C, intermittently warmed fruit had better surface color and flavor and less severe pitting but was slightly less firm (Artés et al. 1998). A short-term treatment in water at 39–45°C appears also to be an effective method to reduce CI and decay in tomatoes, while contributing to normal fruit ripening and overall good eating quality (McDonald et al. 1999). However, exposure of tomatoes to 38°C for 24 hours resulted in severe injury, whereas fruit heated to 34°C was only slightly injured and developed better color. Heat injury in tomato fruit is characterized by scalding, irregular ripening and color development, brown spots, cracking, fluid leakage, and development of decay (Soto-Zamora et al. 2005b).

Disease is the greatest cause of market losses of fresh tomatoes and represents 60% of losses at the retail level and 80% at the consumer level (Ceponis and Butterfield 1979). Losses at the retail level were evaluated as 6.3% and 6.7% in prepacked and bulk fruit, respectively, whereas losses at the consumer level were 7.9% and 4.7%, respectively (Ceponis and Butterfield 1979). Disease in tomato fruit generally develops faster when fruit is held at temperatures above 15–20°C, whereas storage at temperatures lower than 10°C may also contribute to increased decay owing to increased CI-related lesions (Bartz et al. 1991). Decay in mature-green tomatoes held at 2°C increased from approximately 53% after a 10-day storage period to 83% after 14 days (Nussinovitch et al. 1996). Decay development during storage at nonchilling temperatures generally increases with the degree of ripeness and length of storage. Mature-green tomato fruit held at approximately 3°C for 21 days plus 5 days at 18°C became soft, extensive decay developed, and none of the fruit was edible. Conversely, mature-green tomatoes stored at 9°C developed less decay but did not attain good eating quality. Tomatoes with more than 20% color stored at 9°C developed more color but also more decay than those stored when mature-green (Parsons et al. 1960).

The flavor of tomato fruit is perceived through a blend of aroma, taste, and mouth feel and can be defined as a balance among sugars, organic acids, volatile compounds, and free amino acids (Baldwin et al. 1998). However, refrigeration as well as short-term high-temperature storage (45°C for 15 hours) may cause an irreversible decrease in the volatile content and alter the flavor of tomatoes (Baldwin et al. 1998; Boukobza and Taylor 2003). The aroma of ‘Trust’ tomatoes increased slightly during storage, particularly in fruit stored at 20°C (Proulx et al. 2001). Furthermore, the intensity of some flavor impressions such as "tomato-like" and "sweet" increased during storage of tomatoes for 7 days at 20°C; however, the off-flavor components such as "moldy" and "spoiled sweetish" increased as well (Auerswald et al. 1999). For ripe tomatoes stored for 21 days at 20°C, an increase in the attribute "tomato-like" odor, flavor, and aftertaste were detected until 4 days after harvest; however, the intensity of the off-flavor component "moldy" also increased (Krumbein et al. 2004).

Holding mature-green tomatoes at 12.5°C or 15°C for 7 days did not influence the flavor at the table-ripe stage compared with mature-green tomatoes held at 20°C for the same period. However, mature-green tomatoes ripened postharvest were rated lower in fruity-floral aroma and sweetness and rated higher in sourness and off-flavor than fruit ripened on the plant and harvested at the table-ripe stage (Kader et al. 1978). Volatile compounds in tomatoes stored for 3 days at 6°C decreased significantly, and after transfer to ambient temperature some of the compounds were further reduced (Boukobza and Taylor 2002). Storage of mature-green tomatoes at 2°C for 14 days and then ripened at 20°C resulted in decreased levels of flavor volatiles compared to fruit stored continuously at 20°C (McDonald et al. 1999). Likewise, light red tomatoes stored at 5, 10, or 12.5°C for 8–12 days plus 6 hours at 20°C had lower ripe aroma and tomato flavor and higher off-flavors compared to fruit stored at 20°C (Maul et al. 2000). Development of off-flavors in color-break tomatoes stored for 7 days at 10°C compared with storage at 21°C was associated with CI that developed in the tomatoes stored at 10°C (Resurreccion and Shewfelt 1985).

The maximum acceptable weight loss before a tomato becomes unsaleable has been reported to range from 6 to 7% (Hruschka 1977; Robinson et al. 1975). However, three-fourths of 'Trust' tomatoes had lost less than 6% of their initial weight during storage at various temperatures before they were judged to be unsaleable for other reasons (Proulx et al. 2001). Weight loss was higher for tomatoes stored at 15 or 20°C (2–2.5%, respectively) but was less than 1% for tomatoes stored below 15°C. Shriveling ratings for 'Trust' tomatoes agreed with the values obtained for weight loss, since shriveling, like weight loss, never reached objectionable levels during the 14-day storage period. The tomatoes were kept inside their original plastic clamshell containers and covered with a plastic bag, which resulted in a high relative humidity of 95–98% inside the package and which probably contributed to the low weight loss throughout storage (Proulx et al. 2001). In contrast, when tomato fruit were stored at 20°C with low relative humidity levels (65%), weight loss attained a maximum of approximately 15% after 12 days (Syamal 1990). Rate of weight loss increased in tomatoes stored at 2°C and was comparable to that at 20°C (Syamal 1990). During 7 days at 2°C tomatoes lost 0.8% of their weight, whereas after 14 days they had lost 2.3% (Syamal 1990). Mature-green tomatoes stored for 4 weeks at 12°C and 85% relative humidity lost about 9.8% weight, and after 3 weeks the appearance of the fruit started to deteriorate owing to the development of wrinkles, shrinkage of the skin, and loss of brightness (Bhowmik and Pan 1992). Tomatoes stored at 4 or 10°C and 85% relative humidity lost approximately 5.8% of their initial weight after 30 days (Soto-Zamora et al. 2005a). The rate of weight loss for tomatoes stored at 5 or 12°C was 0.15 and 0.49% per day, respectively, whereas in tomatoes stored at temperatures between 25 and 27°C the weight loss rate increased to 0.68% per day (Javanmardi and Kubota 2006).

Parallel to changes in tomato fruit appearance, compositional changes occur and are also temperature driven. During storage of tomato fruit for 8 days at 20°C, chlorophyll content decreased to negligible levels, whereas lycopene content increased (Syamal 1990; Slimestad and Verheul 2005). Chlorophyll content also decreased in tomato fruit stored for up to 30 days at 4 or 10°C, whereas at 4°C production of lycopene was inhibited (Soto-Zamora et al. 2005a). Synthesis of lycopene depends on the temperature, and it seems to occur at higher rates between 12 and below 30°C, whereas at 32°C lycopene synthesis is completely inhibited (Dumas et al. 2003). For example, lycopene content increased during storage of tomatoes for 3 weeks at 20°C, but no changes were observed in fruit stored at 4°C during the same period (Slimestad and Verheul 2005). Similarly, in tomato fruit stored at 25°C, lycopene concentration increased over time compared with storage at 5 or 12°C (Javanmardi and Kubota 2006; Kubota et al. 2006), whereas at 30°C the formation of lycopene was inhibited (Brandt et al. 2006). Lycopene in tomatoes stored at temperatures between 25 and 27°C for 7 days was significantly greater than in tomatoes stored at either 5 or 12°C; however, at 12°C the synthesis of lycopene was much higher than at 5°C (Javanmardi and Kubota 2006).

After 12 or 21 days at 20°C, the acidity of tomato fruit decreased, whereas an increase in total soluble solids content was observed (Krumbein et al. 2004; Syamal 1990). In red harvested tomatoes, acidity increased by 22% during 4 days at 20°C and decreased thereafter, whereas reducing-sugar content remained relatively constant during 7 days of storage. Decreased acidity of tomato fruit after storage for 7 days at 20°C resulted in increased intensity of impressions such as "sweet," "spoiled sweetish," "tomato-like," and "moldy" (Auerswald et al. 1999). Tomato fruit stored at 10°C has, in general, lower sugar-to-acid ratios than that held at higher temperatures (Kader et al. 1978). After 12 days, fruit ripened at 20°C had a higher content of reducing sugars and lower acidity than that held for 7 days at 12.5°C. In fact, tomatoes harvested mature-green or light pink and ripened at 20°C were sweeter and with more "tomato-like" flavor than those held for 7 days at 12.5°C. However, tomato fruit held for 7 days at 5°C had higher acidity and lower reducing sugars, sugar-to-acid ratio, and volatile contents compared to fruit held at nonchilling temperatures (Kader et al. 1978). Tomatoes ripened on the vine and stored for 4 weeks at 22°C had lower acidity and firmness and higher sugar-to-acid ratio and volatile levels than fruit stored at 4°C (Kader et al. 1978).

Ascorbic acid content increased in tomato fruit stored for 8 days at 20°C, but decreased thereafter (Syamal 1990). Color-break tomatoes stored for 10 days at 21°C showed the highest content of ascorbic acid with greatest retention during storage, compared with storage at 1.6 or 10°C (Scott and Kramer 1949). For tomato fruit stored at 4 or 10°C, ascorbic acid content increased initially but then decreased (Soto-Zamora et al. 2005a). Ripening of tomato fruit at high temperatures leads to a decrease in ascorbic acid content owing to oxidation (Dumas et al. 2003). Although ascorbic acid content may increase during storage of tomatoes harvested at earlier stages of ripeness, it never attains the levels found in vine-ripened fruit (Scott and Kramer 1949). Tomatoes harvested green and ripened at 20°C contained about 55–65% of the ascorbic acid content relative to those harvested at the table-ripe stage (Kader et al. 1977).

Time and Temperature Effects on the Visual Quality of 'DRW 7299' Greenhouse-Grown Tomatoes

'DRW 7299' tomatoes shown in Figures 5.1–5.9 were harvested at three-quarters color (light red; i.e., more than 60% of the surface shows pinkish-red or red color) from a commercial operation in Wellborn, Florida, during the spring season (i.e., April). Promptly after harvest, fresh tomatoes were stored at five different temperatures (2.0 ± 0.3°C, 5.0 ± 0.2°C, 9.4 ± 0.4°C, 14.40 ± 0.4°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Postharvest changes in the visual quality of greenhouse-grown tomatoes cultivar 'DRW 7299' harvested at the light red stage are not only associated with changes in fruit coloration but also with changes in fruit texture and development of decay. Such changes depend on the storage temperature and are in general accentuated as storage progresses.

'DRW 7299' tomatoes stored at 2°C maintain acceptable visual quality for 6 days. After 8 days a subtle water-soaked translucent lesion becomes apparent at the blossom-end of the fruit, which increases in size and depth as storage progresses (Figure 5.1). After 2 days, the remaining green color on the tomato surface changes to a uneven reddish-orange color, which is maintained throughout storage. After 27 days at this temperature, the fruit develops an irregular reddish-orange coloration and never becomes completely red. Tomatoes stored continuously at 0°C for 8 or more days develop pitting upon transfer to 20°C for 2 days (Figure 5.2); however, the color of the fruit remains practically unchanged and the tomatoes develop blotchy discoloration. Fruit softening is evident after 18 days at 0°C, and after 22 days the internal tissues appear translucent and leaky.

Although tomatoes stored at 5°C maintain acceptable visual quality during 27 days of storage, the fruit develops blotchy discoloration without ever developing full-red color (Figure 5.3). After 22 days at 5°C, softening of the fruit is evident. Upon transfer to 20°C for 2 additional days, the color of the fruit remains reddish-orange, never changing to a full-red color (Figure 5.4). In addition, the first pitting develops after 8 days at 5°C, and after 14 days the first brownish decayed spots appear on the fruit surface, increasing with further exposure duration at 5°C. The internal fruit tissues develop a translucent and leaky appearance after 25 days at 5°C, and after 27 days the fruit is very soft.

'DRW 7299' greenhouse-grown tomatoes harvested at the light red stage and stored at 10°C maintain acceptable visual quality for 33 days (Figure 5.5). The fruit develops normal red coloration during storage. After 33 days, the tomatoes are fully ripe, but become somewhat soft, as they yield to moderate finger pressure. No decay was observed in any fruit stored at this temperature during 33 days of storage.

Color development and fruit softening occur rapidly when tomatoes are stored at 15°C. Although 'DRW 7299' tomatoes maintain acceptable visual quality for 33 days at 15°C, the fruit becomes very soft, yielding to slight finger pressure, appears overripe, and the internal tissues are very juicy (Figure 5.6). At this temperature, decay may become a problem, as some fruit may develop moderate to severe decay after 25 days (Figure 5.7).

Tomato fruit stored at 20°C develops an intense red color during storage, and the fruit becomes extremely overripe and soft, yielding easily to slight finger pressure (Figure 5.8). The flesh of the fruit appears extremely juicy, soft, and bland, whereas the skin is tough. After 18 days, some fruit develops sunken lesions owing to internal decay, whereas after 25 days brownish decayed spots and mycelial growth are evident on some of the fruit (Figure 5.9).

Overall, 'DRW 7299' greenhouse-grown tomatoes harvested at the light red stage maintained the best visual quality for the longest period when stored at 10°C (33 days) compared with fruit stored at higher or lower temperatures. The postharvest life of tomatoes stored at 2 or 5°C was reduced to 6 and 8 days, respectively, due to the development of CI-related symptoms, whereas decay reduced the postharvest life of tomatoes stored at 15 or 20°C to 25 and 18 days, respectively.

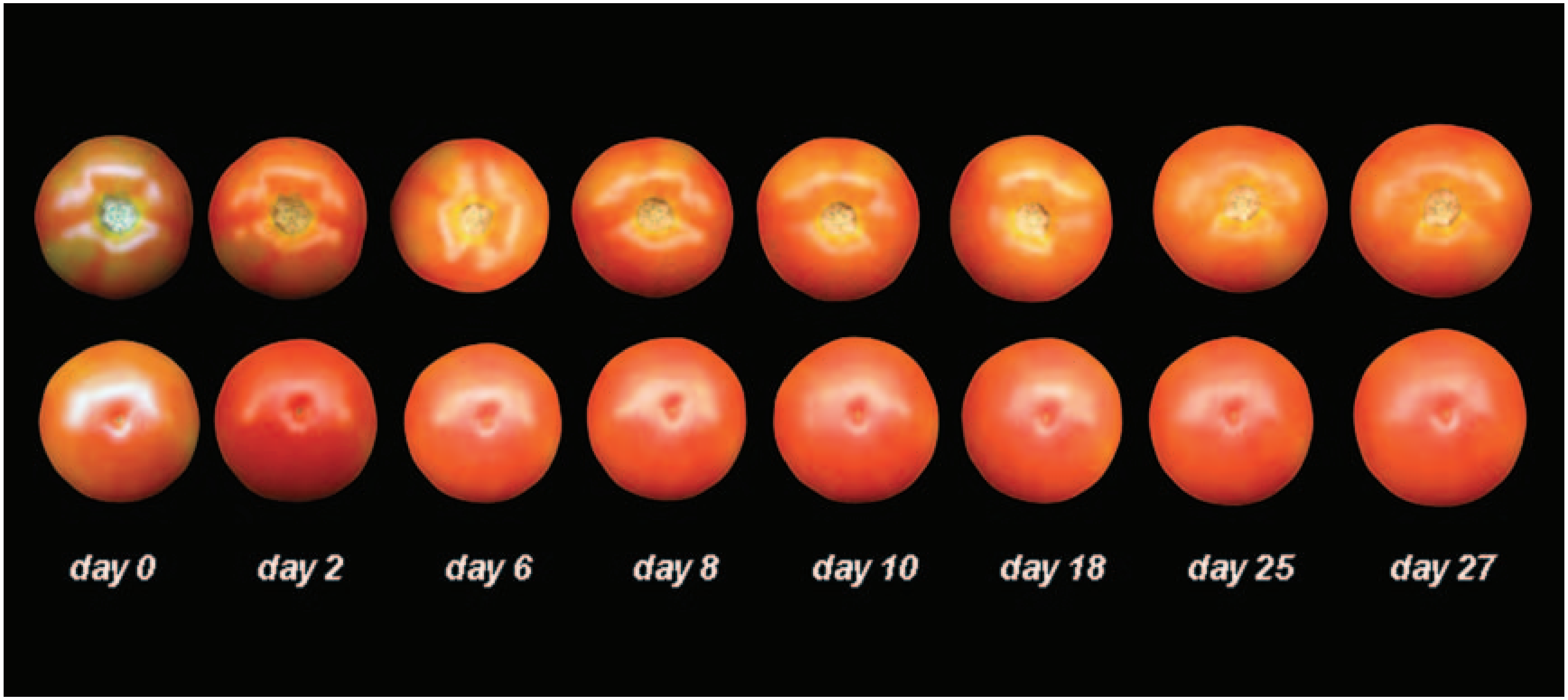
day 0
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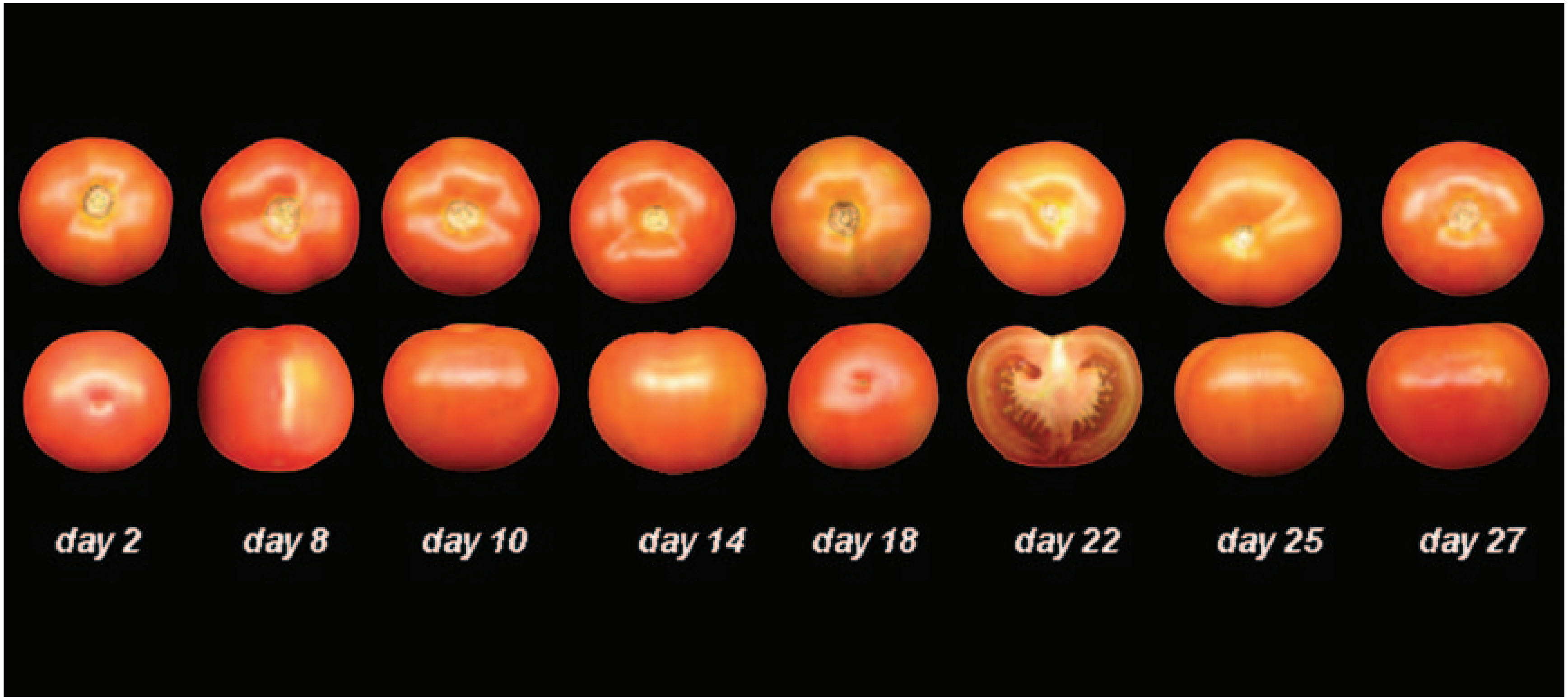
Figure 5.1. Appearance of 'DRW 7299' greenhouse-grown tomatoes stored for 27 days at 2°C. After 8 days, the tomato fruit develops water-soaked translucent lesions at the blossom-end.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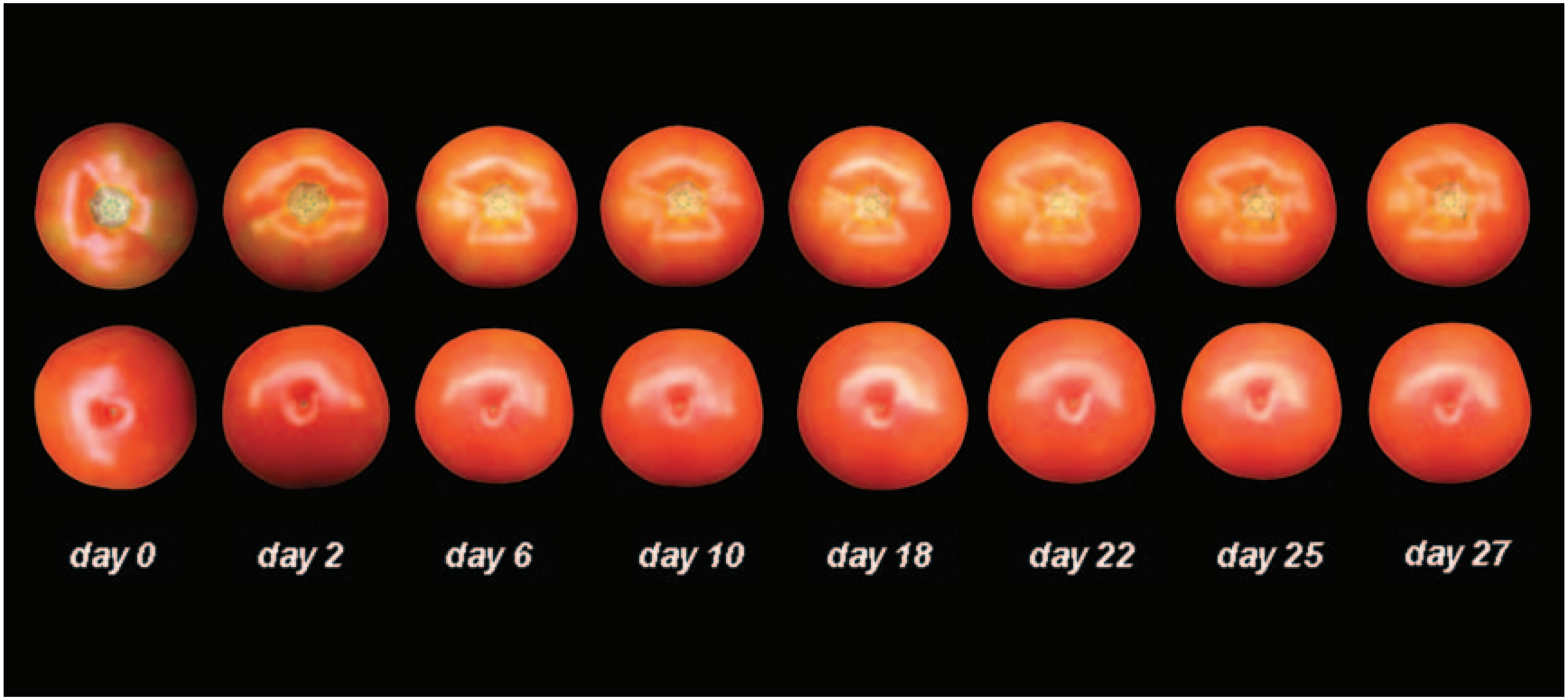
day 27

Figure 5.2. Appearance of ‘DRW 7299’ greenhouse-grown tomatoes stored for 27 days at 2°C plus transfer to 20°C for 2 additional days. The first signs of CI develop after 8 days at 2°C plus transfer to 20°C for 2 additional days.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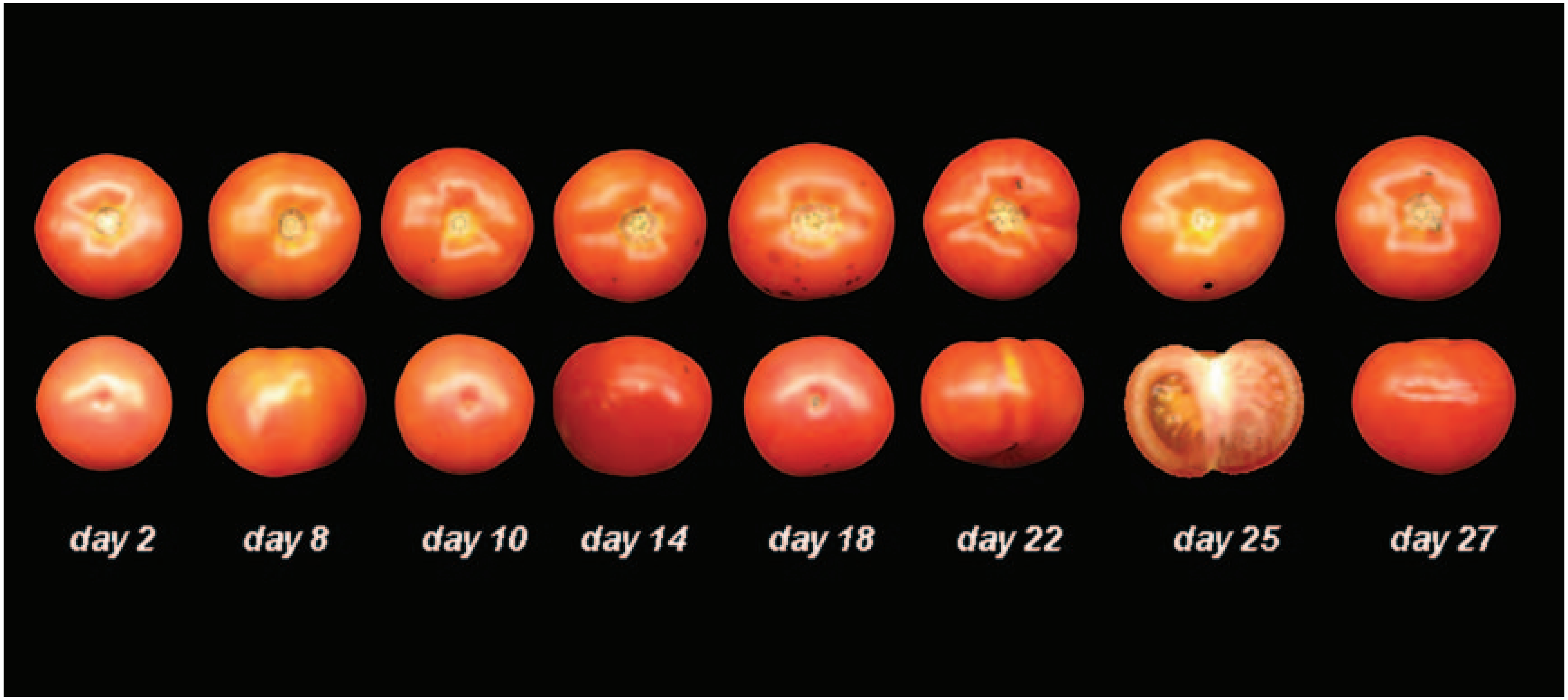
day 25
day 27

Figure 5.3. Appearance of 'DRW 7299' greenhouse-grown tomatoes stored for 27 days at 5°C. Tomato fruit maintains acceptable visual quality for 27 days, yet ripening is uneven and the fruit develops blotchy discoloration.


day 2
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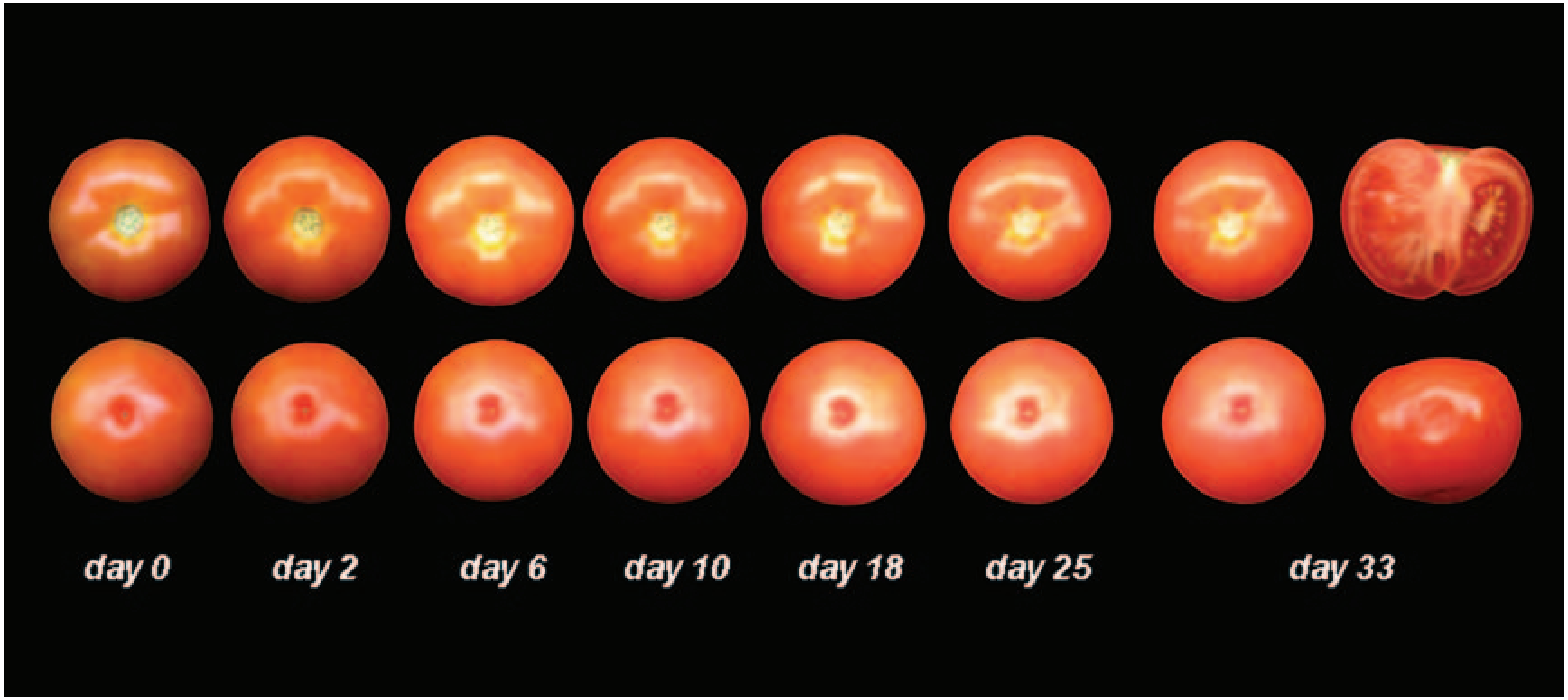
day 22
day 25
day 27

Figure 5.4. Appearance of 'DRW 7299' greenhouse-grown tomatoes stored for 27 days at 5°C plus transfer to 20°C for 2 additional days. The first signs of CI develop after 8 days at 5°C plus transfer to 20°C for 2 additional days.


day 0
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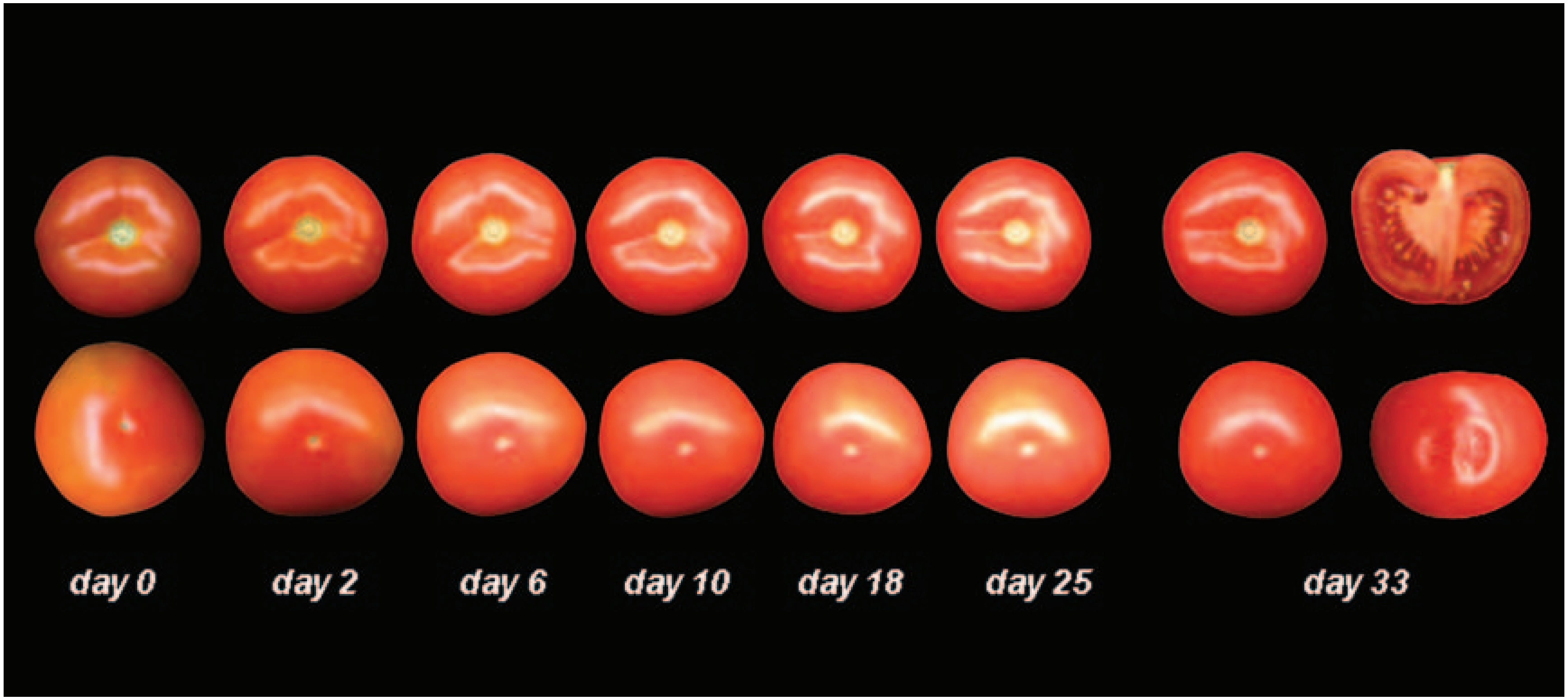
day 33

Figure 5.5. Appearance of 'DRW 7299' greenhouse-grown tomatoes stored for 33 days at 10°C. Tomato fruit maintains acceptable visual quality for 33 days, yet after that time the fruit is soft and very ripe.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day 10
day 18
day 25
day 33

Figure 5.6. Appearance of 'DRW 7299' greenhouse-grown tomatoes stored for 33 days at 15°C. Tomato fruit maintains acceptable visual quality for 33 days, yet after that time the fruit is very soft and appears overripe.

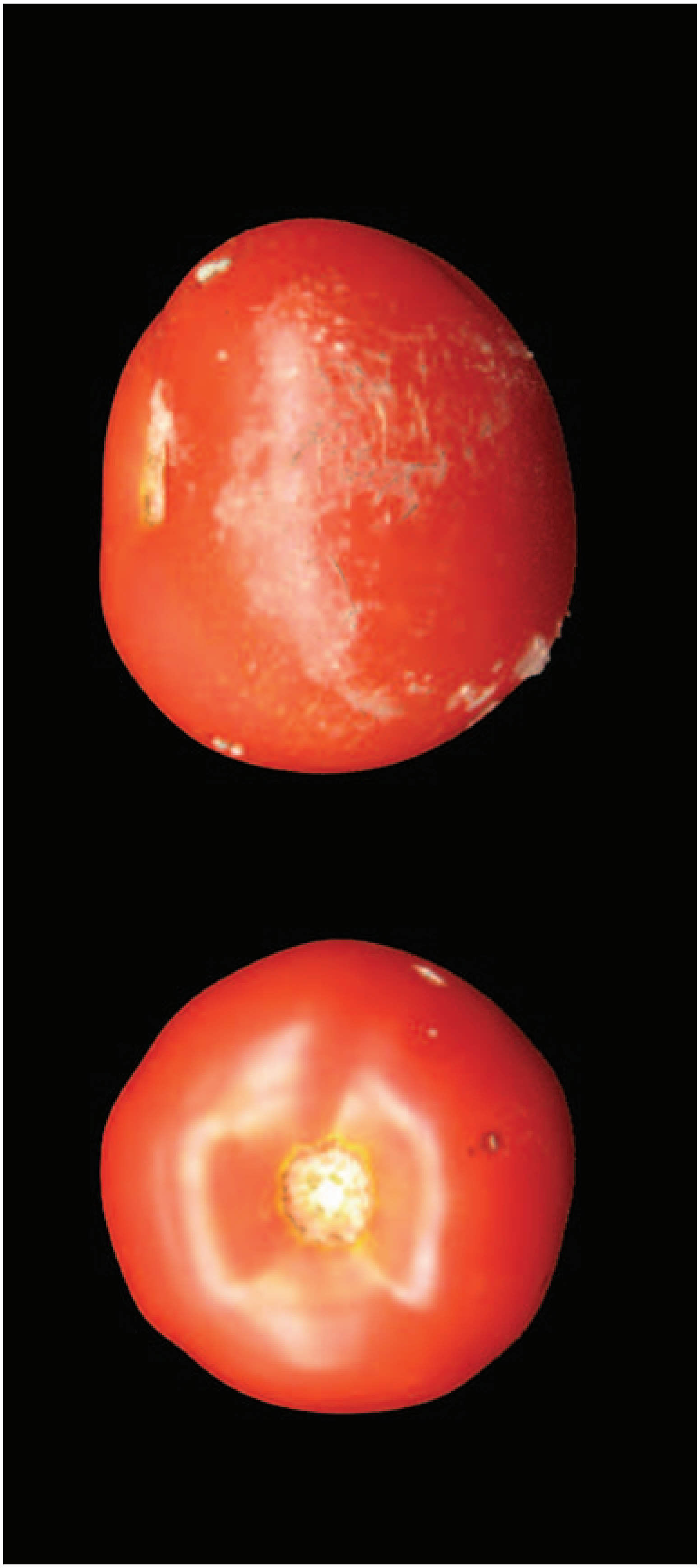
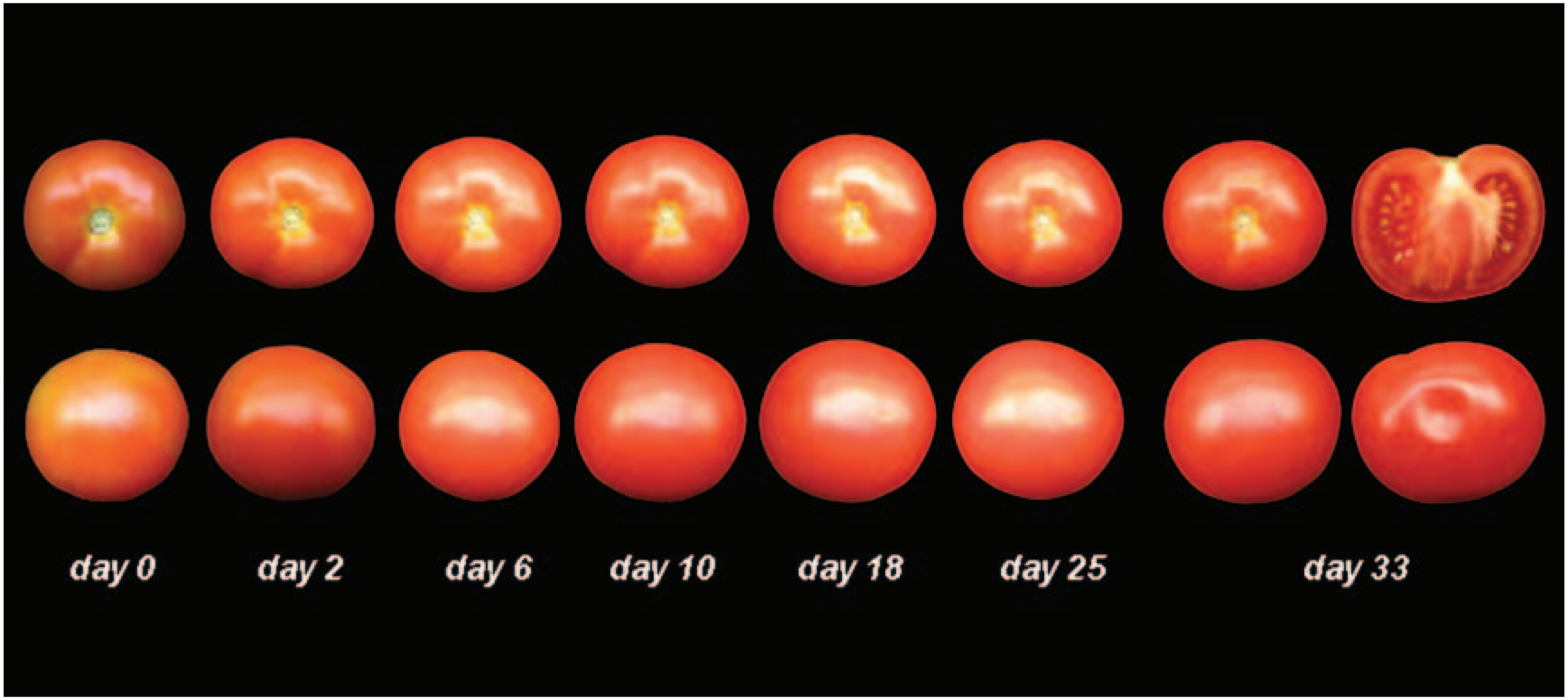


Figure 5.7. Decay of 'DRW 7299' greenhouse-grown tomatoes stored for 25 days (left) and 33 days (right) at 15°C.


day 0
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day 10
day 18
day 25
day 33

Figure 5.8. Appearance of 'DRW 7299' greenhouse-grown tomatoes stored for 33 days at 20°C. Tomato fruit maintains acceptable visual quality for 33 days, yet after that time the fruit is extremely soft and overripe.

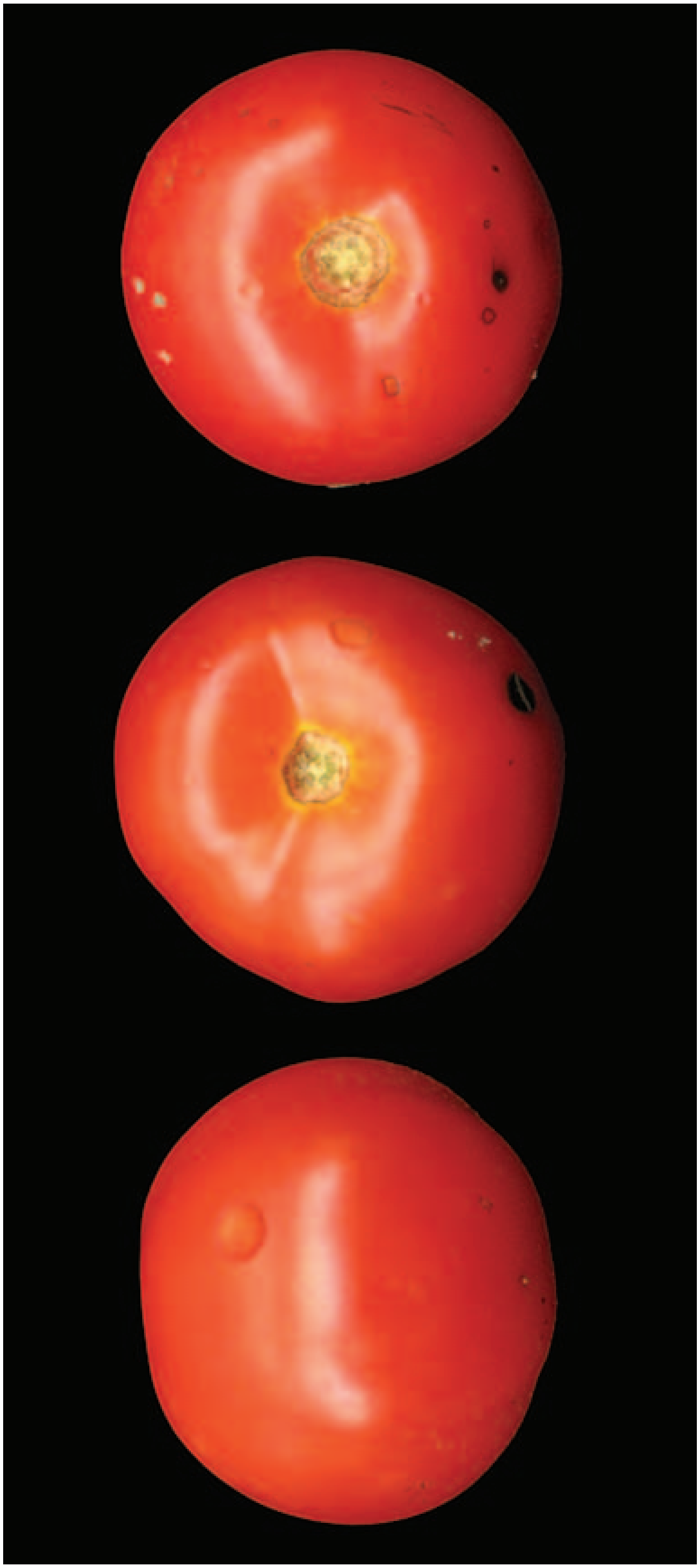

Figure 5.9. Decay of 'DRW 7299' greenhouse-grown tomatoes stored for 18 days (left), 25 days (center), and 33 days (right) at 20°C.

CAPE GOOSEBERRY

Scientific Name: *Physalis peruviana L.*
Family: Solanaceae

Quality Characteristics

Cape gooseberry fruit, also known as goldenberry, is grown all over the Andes Mountains of South America and was previously used by the Incas (Hewett 1993; National Academy of Sciences 1989). Cultivation in Europe started during the seventeenth century in the United Kingdom and later extended to South Africa, Australia, and New Zealand. The plant was grown by early settlers of the Cape of Good Hope before 1807 and is now commercially cultivated in South Africa. Although commercial production has been developing in Central and South Africa, Australia, New Zealand, and India, production of cape gooseberry is still very small and the fruit is usually supplied to local markets (McCain 1993).

The fruit of cape gooseberry is a small, smooth, and waxy round berry that measures on average 1.25–2.5 cm in diameter. The flesh is sweet and juicy and full of small, flat, yellowish seeds. The fruit is encased in a paper-like tan husk, and when fully ripe the fruit and the husk fall naturally from the plant (McCain 1993; Sarkar et al. 1993). Cape gooseberry fruit is considered fully ripe when the color turns from green to orange or yellow-gold. In addition to changes in color, as cape gooseberry fruit ripens, firmness significantly decreases from the green, unripe stage to the full orange-yellowish stage. Ripe, yellowish-orange berries were reported to be about 35% less firm than mature, yellowish-green fruit. Fruit with firmness levels lower than 4.5 N (Newtons) was considered unacceptable for sale (Trinchero et al. 1999). Simultaneously with this decrease in fruit firmness and accumulation of sugar, an increase in total soluble pectic substances was observed during fruit ripening (Majumder and Mazumbar 2001, 2002).

The maturity of cape gooseberries can be assessed visually from the external color, which changes from green to yellow or orange as the fruit ripens, but changes in the color of the calyx are not indicative of ripening of the fruit (FAO 2001; Fischer et al. 1997). Changes in color of the fruit during ripening were associated with chlorophyll breakdown and carotenoid accumulation, mainly β-carotene (Fischer et al. 2000; Trinchero et al. 1999). Although cape gooseberries may be harvested partially green and ripened during storage, that fruit will never develop the sweet taste of vine-ripened fruit (McCain 1993; Sarkar et al. 1993). As cape gooseberry fruit ripens, sugar content, total soluble solids content, soluble solids-to-acidity ratio, and ascorbic acid content increase, whereas starch content decreases continuously until the fully ripe stage. Acidity increases during fruit maturation in early stages of development, but then decreases constantly until the fruit attains the fully ripe stage (Fischer and Lüdders 1997; Fischer et al. 1997; Sarangi et al. 1989). As the fruit ripens, the ratio of sucrose-to-glucose-to-fructose changed from 1 : 33 : 22 at the green and small berry stage to 1 : 1.6 : 1.4 when the calyx had almost attained its final size, but both calyx and berry were still green. The sugars ratio then changed to 1 : 0.53 : 0.57 when the berry was green-yellow and the calyx pale yellow and not yet dry, and when the berry reached the dark yellow stage and the calyx was brown, dry, and paper-like, the sucrose decreased very slightly in favor of glucose and fructose, yielding a ratio of 1 : 0.63 : 0.70. However, at this stage of development a decline in total sugar and citric acid contents was observed (Baumann and Meier 1993).

At the time of harvest (i.e., brilliant orange coloration), cape gooseberry may contain more than 6% total sugars, 8–16% total soluble solids content, 0.73–0.92% acidity (mainly citric acid), and a pH between 3.6 and 4.7 (Fischer et al. 2000; Klinac 1986; Mayorga et al. 2002; Mazumdar and Basu 1979; National Academy of Sciences 1989; Wolff 1991). When fully ripe, cape gooseberry has a delicious sweet flavor, described by some as a tangy pineapple or grape-like flavor, and by others as a nutty and tomato- or plum-like flavor with a creamy-fruity odor note. The husk is bitter and not edible (California Rare Fruit Growers 1997; Hewett 1993; Mayorga et al. 2001; McCain 1993; Morton 1987; Wolff 1991). Overall, good quality fruit should be orange-gold, firm, fresh in appearance, and with a smooth and shiny skin, and when the calyx is present the peduncle should not exceed 25 mm in length. For best quality, the soluble solids content of the fruit should be at least 14% (FAO 2001).

The cape gooseberry fruit is very rich in vitamins B and C, carotene, and polyphenols (Hewett 1993; McCain 1993; Morton 1987). Cape gooseberries contain on average 78.9%

water, 11.5% carbohydrates, 0.9–1.8% pectin, 0.054% protein, 0.16–2% fat, 3.2–4.9% fiber, 1.613–3.355 mg of β-carotene, and 30.0–54 mg of vitamin C per 100 g fruit fresh weight (Fischer et al. 2000; Mazumdar and Basu 1979; Morton 1987; Ramadan and Morsel 2005; Sarkar and Chattopadhyay 1993).

Optimum Postharvest Handling Conditions

The postharvest life of cape gooseberry fruit is longer when the husk remains attached, and the fruit may last several months without refrigeration if kept dry (McCain 1993; Morton 1987). If dried first at 30°C until the calyx is crisp, fruit with intact calyces can be stored at temperatures lower than 35°C for 4–5 months. Removing berries from the calyces is labor intensive, increases damage, and reduces fruit postharvest life. Fruit with husks attached was also successfully stored at temperatures below 2°C for 4–5 months before marked shrinkage and collapse occurred (Klinac and Wood 1986; National Academy of Sciences 1989). Although the only reports found on the postharvest handling conditions for cape gooseberry state that the fruit may be stored without refrigeration for up to 5 months, Figure 5.17 shows that after 32 days at 20°C shriveling becomes evident in some of the berries.

Temperature Effects on Quality

To date, no extensive research has been done on cape gooseberry fruit, and limited information is found in the literature regarding postharvest practices and recommendations for this fruit. Therefore, little is known about the fruit postharvest quality and compositional changes when cape gooseberries are stored under different environmental conditions.

Sarkar et al. (1993) reported that total sugar, reducing sugars, and total soluble solids contents increased in mature-green and half-ripe cape gooseberry fruit during storage, whereas total soluble solids content, acidity, and ascorbic acid content decreased in ripe fruit during storage. However, mature-green fruit were more acid than ripe fruit, whereas half-ripe and ripe fruit retained appreciable amounts of ascorbic acid after 8 days of storage. The authors concluded that fruit for long-term storage should be harvested at the half-ripe stage (Sarkar et al. 1993).

Time and Temperature Effects on the Visual Quality of 'Goldie' Cape Gooseberry

'Goldie' cape gooseberries shown in Figures 5.10–5.17 were harvested at the mature stage at about 2.5 cm in diameter from a commercial operation in Saint-Augustin-de-Desmaurs, Quebec, Canada, during late summer (i.e., early September). Promptly after harvest, fresh berries were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Because of its particular structure, cape gooseberry fruit quality is difficult to evaluate without damaging the calyx that envelops the berry. Changes in the visual quality of the calyx are not pronounced during storage, regardless of the temperature, and calyx condition is not a very good indicator of the quality of the fruit contained inside the husk. Major changes in cape gooseberry visual quality are related to changes in the color of the berry from a light yellowish-gold or orange to a dark yellowish-gold or orange, as well as shriveling and decay when the fruit is stored at temperatures higher than 10°C. When stored at lower temperatures, decay and pitting of the skin similar to that observed in various chilling-sensitive fruits may develop.

The appearance of the calyx of 'Goldie' cape gooseberries stored at 0°C does not change significantly during storage. The calyx maintains its tan, papery-like appearance throughout storage, with no visual signs of increased dryness (Figure 5.10). The color of the berries changes very slightly during storage and the fruit maintains acceptable visual quality through 64 days of storage. After 74 days, the berries develop a little decay at the stem-end where the calyx is still attached. However, when transferred to 20°C for 2 additional days after exposure to 0°C for 6 days, the berries develop slight surface pitting and discoloration. Although no information was found regarding CI symptoms in cape gooseberries exposed to low temperatures, these symptoms may be associated with some level of chilling susceptibility of the fruit when exposed to 0°C (Figure 5.11).

For cape gooseberries stored at 5°C, slight changes in the calyx occur during storage. After 64 days of storage, the calyx appears dry and lighter in color than at the time of harvest (Figure 5.12). The berries maintain acceptable visual quality through 56 days of storage, but after 64 days a brownish decayed area may develop on some of the berries. Decay continues to increase, and after 74 days some berries develop areas of extensive mycelial growth, whereas the flesh becomes brownish-black at the stem-end (Figure 5.13). Upon transfer to 20°C for 2 additional days after storage for 12 days at 5°C, the berries develop slight pitting and brownish discoloration of the skin (Figure 5.14).

Cape gooseberries stored at 10°C maintain acceptable visual quality for 64 days, but after 74 days shriveling is noticeable (Figure 5.15). The color of the husk changes from dark to light tan and appears dry after 74 days of storage. After 86 days, the berries develop severe decay at the stem-end, where the fruit is attached to the calyx. Fruit stored at 10°C and then transferred to 20°C for 2 additional days does not show any putative CI symptoms such as those observed on fruit stored at 0 or 5°C, and the visual quality remains similar to that of cape gooseberries stored continuously at 10°C.

The color of the husk and berry changes during storage at 15°C; the husk appears lighter and drier after 86 days of storage, and the berries develop a deeper yellowish-orange coloration (Figure 5.16). Cape gooseberries maintain acceptable quality for 56 days at 15°C, but after 64 days the berries appear less glossy than at the time of harvest, and the first signs of shriveling become evident. After 86 days, the berries appear extremely shriveled, and the color changes to a dull, dark orange. The husk is completely dry at this time and breaks easily.

Shriveling of the berry and dryness of the husk develop faster and are more severe in fruit stored at 20°C than at 15°C. After 32 days, the first signs of shriveling become evident, and as storage progresses shriveling increases significantly (Figure 5.17). After 64 days, the berries are completely shriveled and dry, whereas the husk becomes lighter in color and dry in appearance.

Compared with other temperatures, 'Goldie' cape gooseberries maintain the longest postharvest life and best visual quality when stored at 10°C, maintaining acceptable quality for 64 days. Storage at 0 or 5°C reduces the postharvest life of the fruit to only 6 and 12 days, respectively, owing to development of skin injury and discoloration, which are probably the result of CI, upon transfer to ambient temperature. Storage at 15 or 20°C resulted in accelerated shriveling and development of decay and reduced the postharvest life of cape gooseberries to 56 and 32 days, respectively.

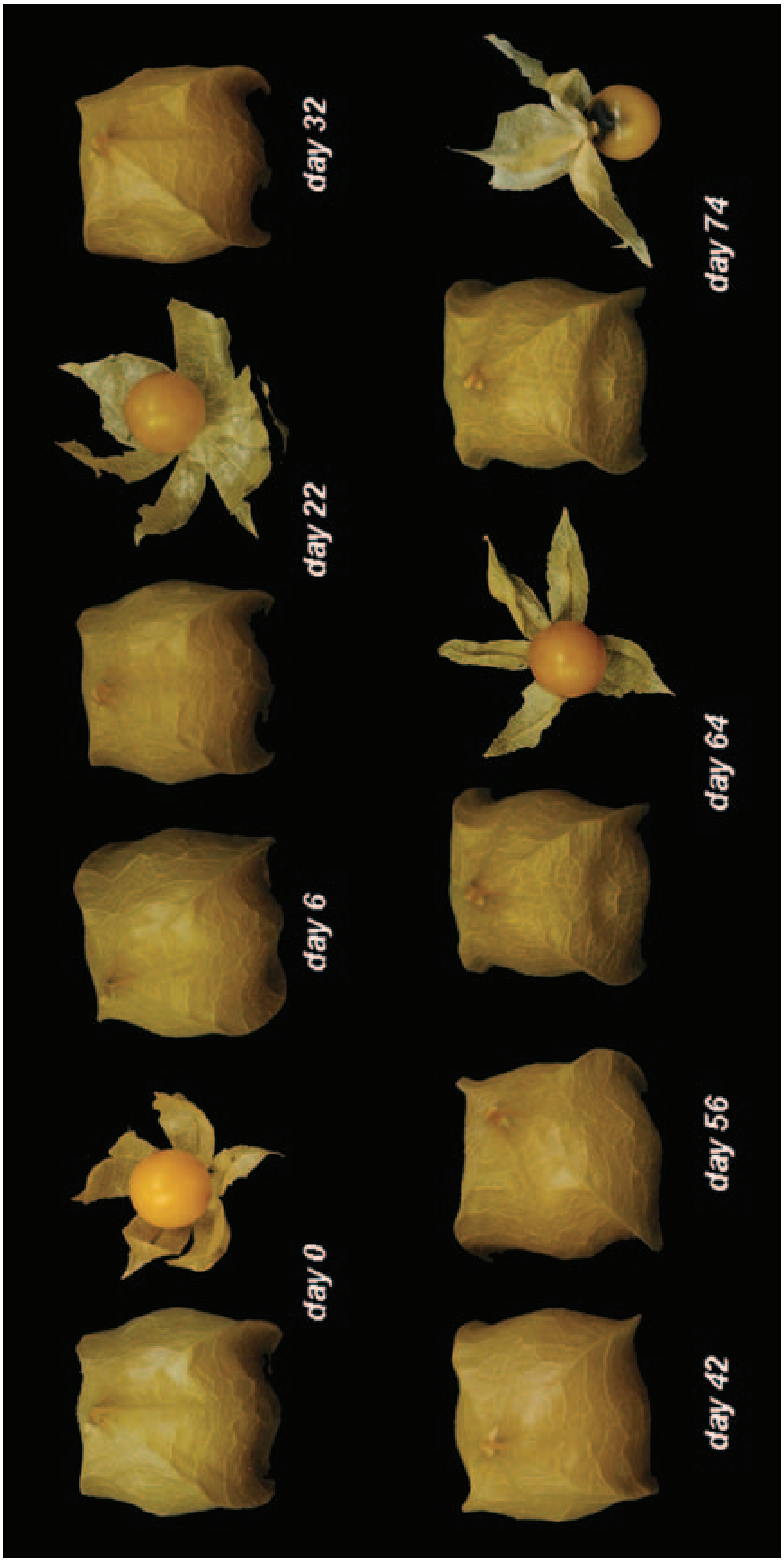
day 0
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Figure 5.10. Appearance of 'Goldie' cape gooseberries stored for 74 days at 0°C. After 74 days, decay develops at the stem-ends of the fruit adjacent to the calyx.

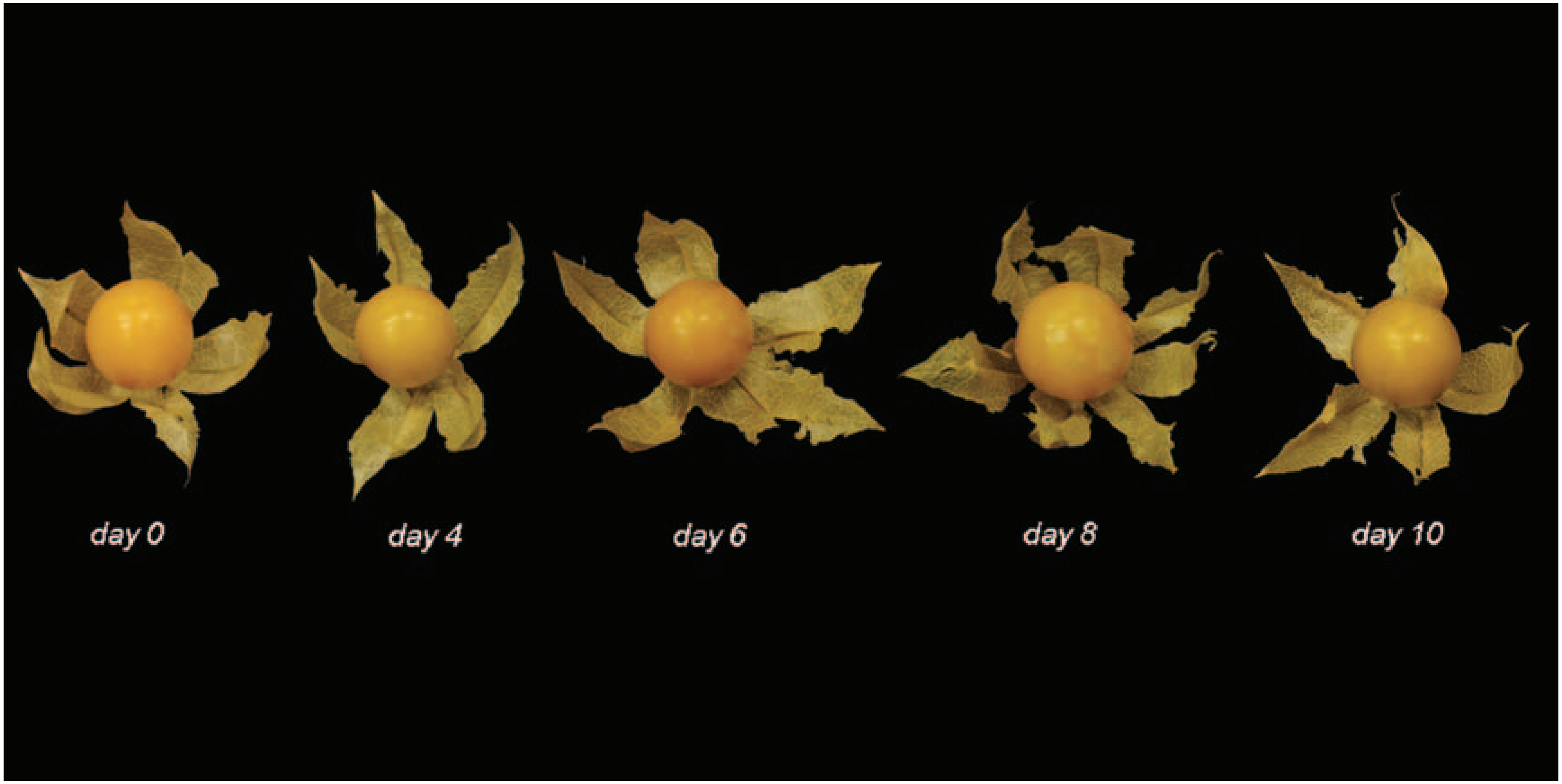
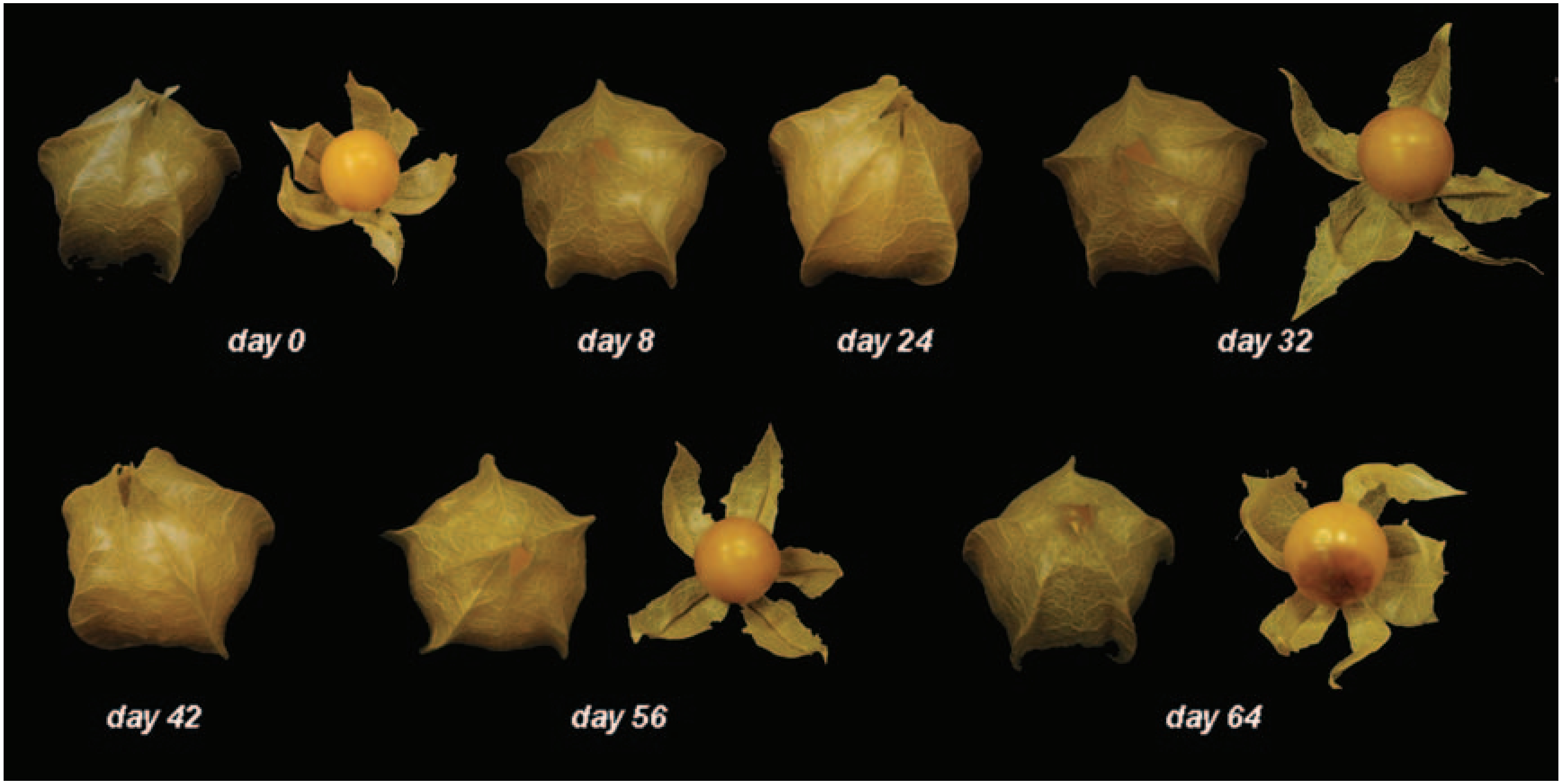


Figure 5.11. Appearance of 'Goldie' cape gooseberries stored for 10 days at 0°C plus transfer to 20°C for 2 additional days. Surface pitting and discoloration are apparent after 6 days at 0°C plus transfer to 20°C for 2 additional days.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day 64

Figure 5.12. Appearance of 'Goldie' Cape gooseberries stored for 64 days at 5°C. After 64 days, brownish decayed areas develop on the surface of the fruit.

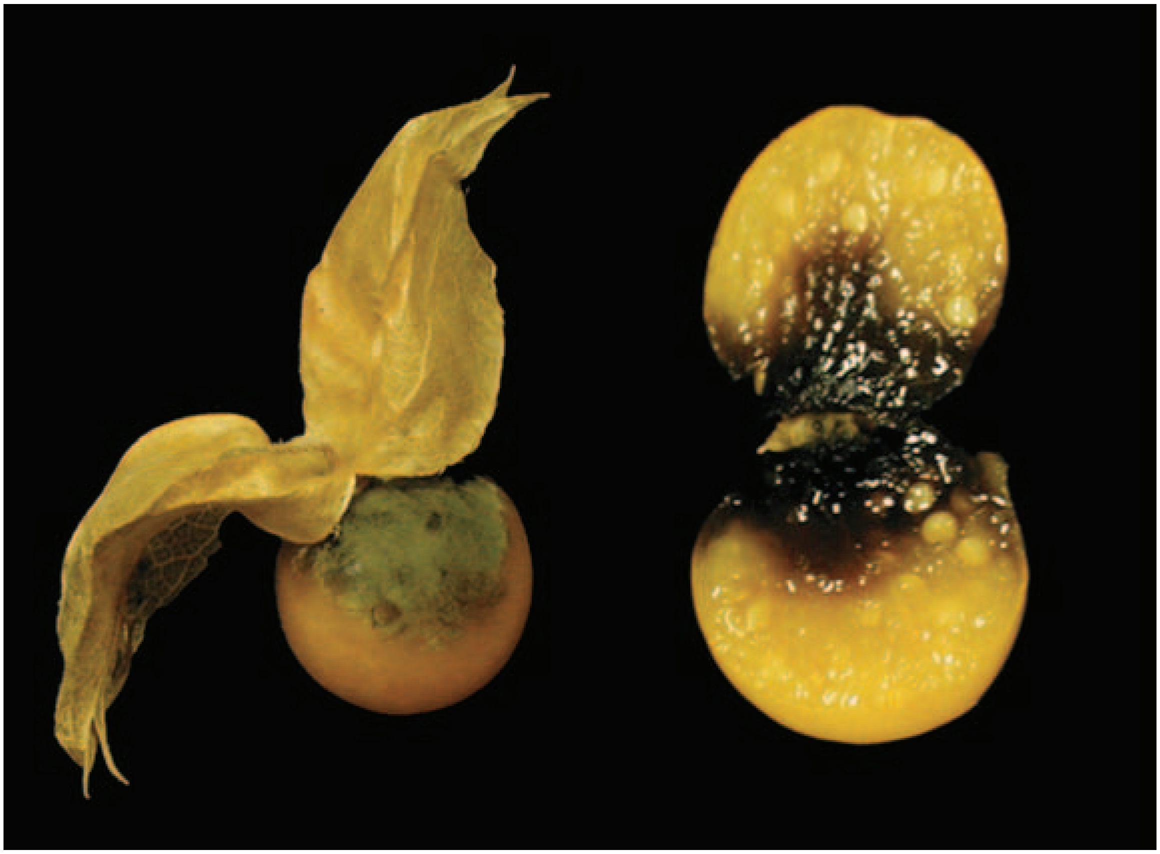

Figure 5.13. Decay of 'Goldie' Cape gooseberries after storage for 74 days at 5°C.

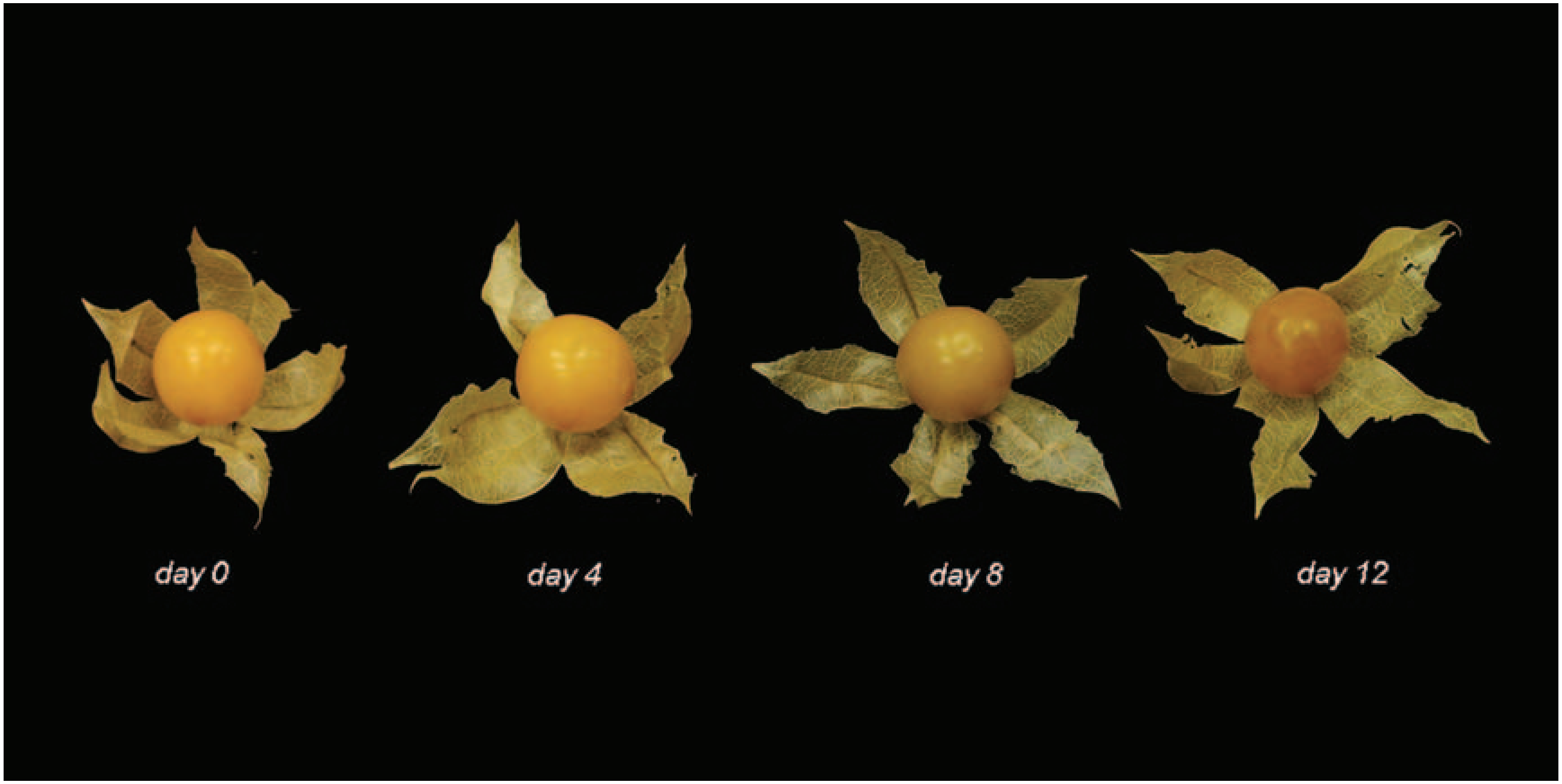

Figure 5.14. Appearance of 'Goldie' cape gooseberries stored for 10 days at 5°C plus transfer to 20°C for 2 additional days. Surface pitting and discoloration are apparent after 12 days.

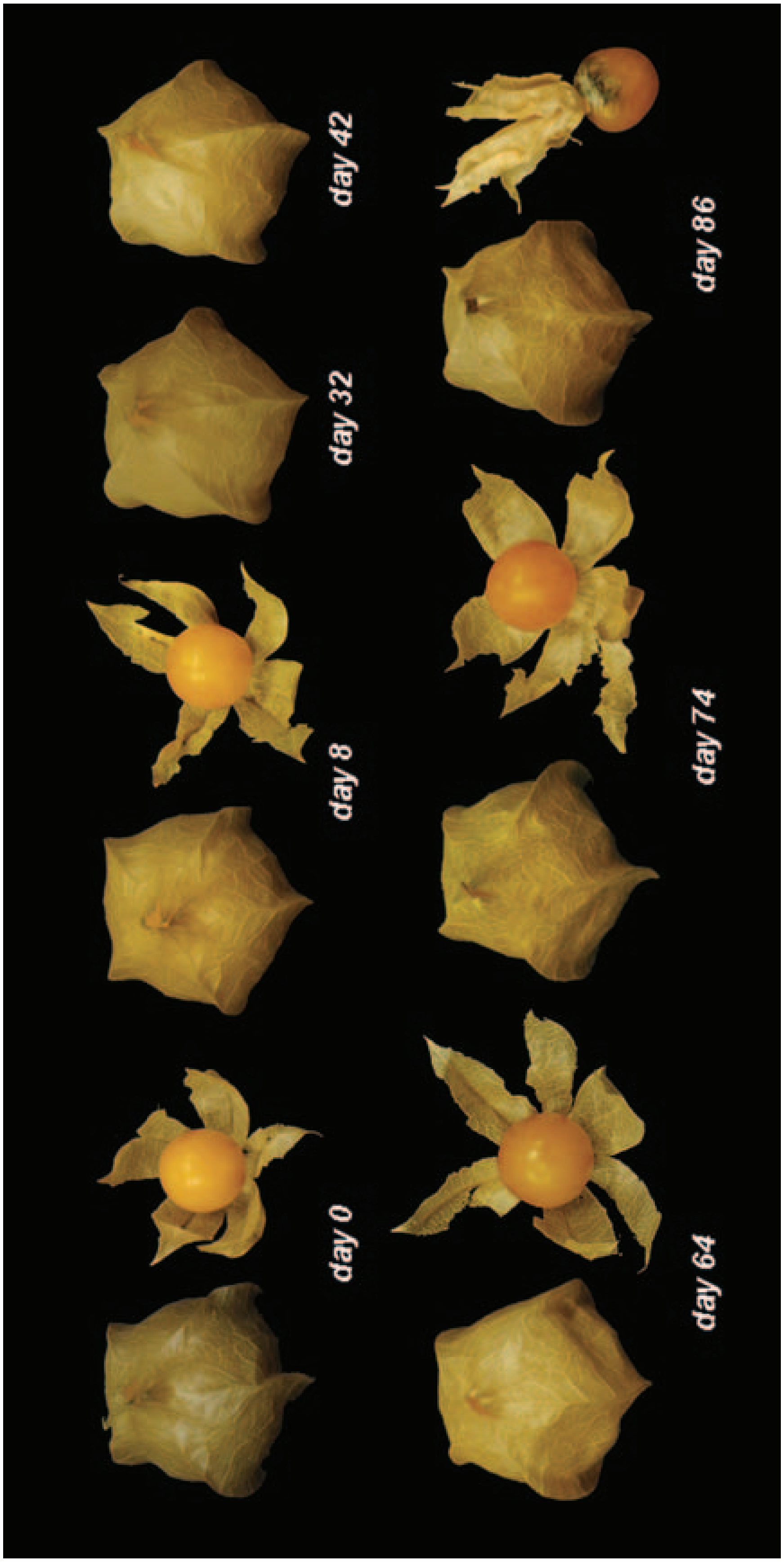
day 0
day 8
day 32
day 42
day 64
day 74
day 86

Figure 5.15. Appearance of 'Goldie' Cape gooseberries stored for 86 days at 10°C. After 74 days, shriveling becomes apparent and, after 86 days, the berries develop severe decay at the stem-end.

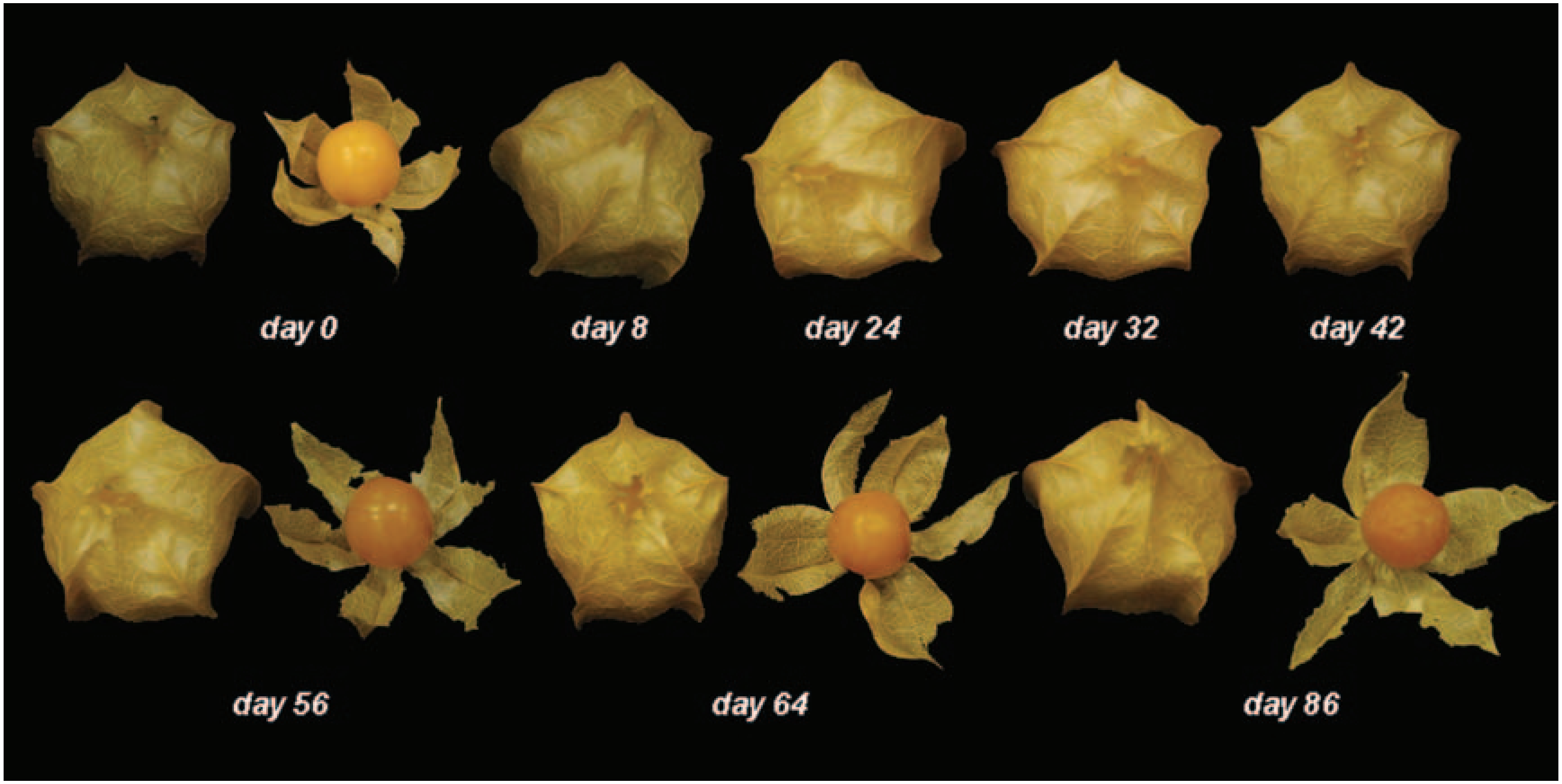
day 0
day 8
day 24
day 32
day 42
day 56
day 64
day 86

Figure 5.16. Appearance of 'Goldie' Cape gooseberries stored for 86 days at 15°C. After 86 days, the berries appear extremely shriveled and the color changes to a dull, dark orange.

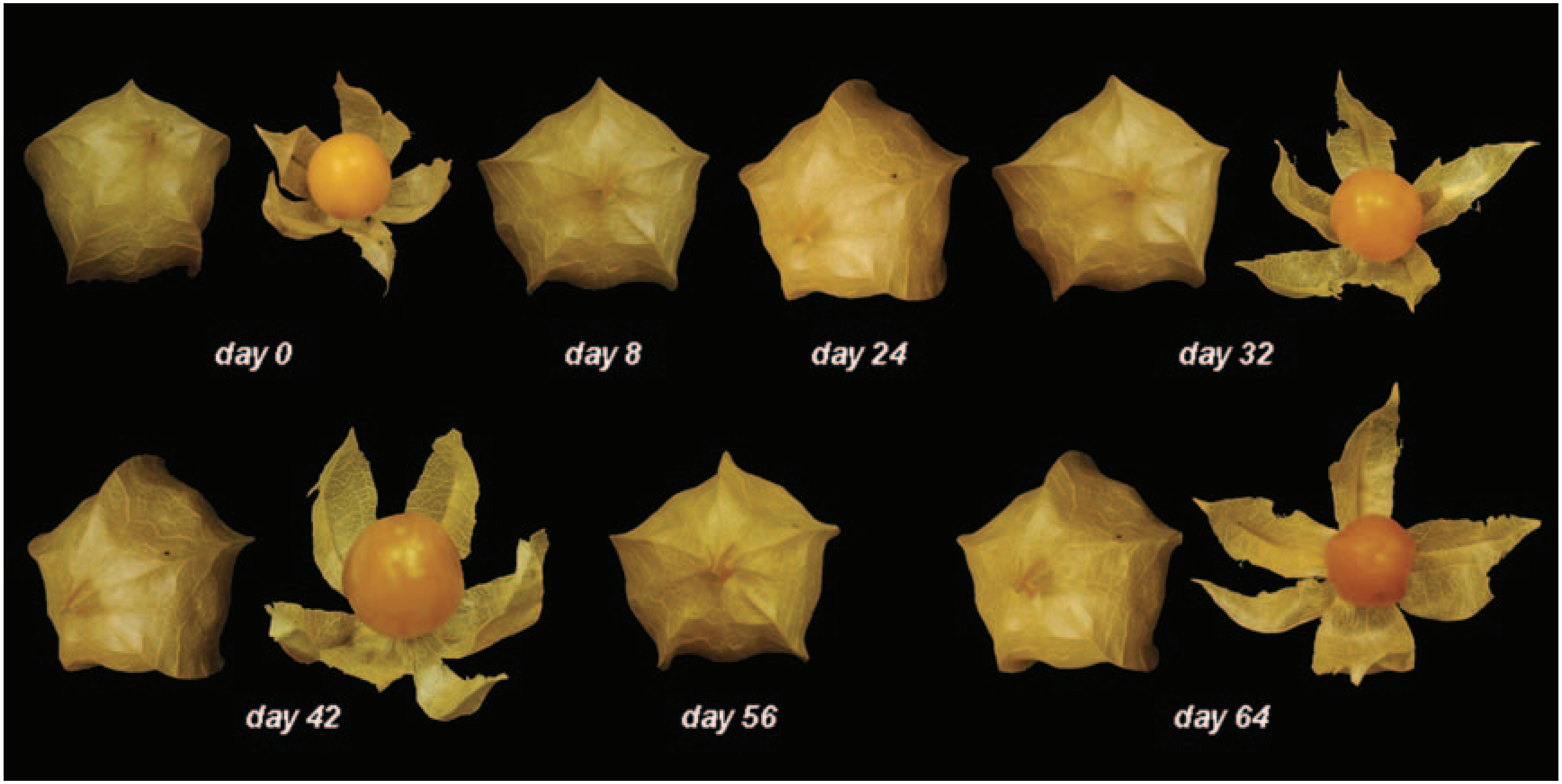
day 0
day 8
day 24
day 32
day 42
day 56
day 64

Figure 5.17. Appearance of 'Goldie' Cape gooseberries stored for 64 days at 20°C. After 64 days, the berries are completely shriveled and dry, while the husks become lighter in color and dry in appearance.

GREEN BELL PEPPER

Scientific Name: *Capsicum annuum* L.
Family: Solanaceae

Quality Characteristics

Green bell pepper is the most frequently used type of pepper. The green bell pepper pod is an unripe fruit, fully developed in terms of size and seed viability. Although all bell peppers are green when unripe, different varieties may develop red, yellow, orange, or purple coloration during ripening. Green, red, and yellow peppers are the most common peppers sold at the market, followed by orange, purple, and other unusual colors (Frank et al. 2001). Bell peppers harvested before the ripe color stage (i.e., green) are in general less expensive than ripe peppers because on-the-plant ripening of colored peppers leads to greater losses owing to decay and various other types of damage. In addition, green bell peppers can better withstand transport and have a longer postharvest life than ripe colored fruit (Frank et al. 2001; Fox et al. 2005).

Although bell pepper is considered to be a non-climacteric fruit due to its very low endogenous rate of ethylene production (González-Aguilar 2004), when harvested at 10–30% coloration (i.e., the "color-break" stage) and ripened off the plant at 20°C, fruits of red and yellow bell pepper varieties developed similar appearance (i.e., red or yellow color) and compositional attributes (i.e., total soluble solids, acidity, and pH) as those ripened on the plant (Molinari et al. 1999). Exposure of bell peppers with 10–60% red color development to 100 μL/L ethylene during storage at 20°C resulted in accelerated chlorophyll breakdown and increased carotenoid production after 3–6 days, compared with fruit stored in air at the same temperature, without altering the flavor, ascorbic acid content, or antioxidant capacity (Fox et al. 2005). Nonetheless, when harvested before the color-break stage and stored at 22°C, peppers did not develop a fully red color even when exogenous ethylene was applied (Krajayklang et al. 2000).

Surface color change was reported to be the major indicator of bell pepper maturity because of its close association with several other attributes, namely total soluble solids content and fruit firmness (Tadesse et al. 2002). The time until full coloration and rate of color changes on the plant are dependent on the environmental conditions during fruit development in the field, and on cultivar characteristics. For example, 'Domino' peppers ripened on the plant remained green for 7–8 weeks before starting to change color from green to red. Pericarp thickness also increased in 'Domino' pepper fruit ripened on the plant and was positively correlated with fruit firmness (Tadesse et al. 2002). At harvest, green peppers are generally firmer and have higher water potential and insoluble pectins and lower water-soluble pectins than red peppers (Lurie et al. 1986; Sethu et al. 1996). In addition, a high positive correlation was found between the firmness of bell peppers at harvest and their postharvest life (Janse 1989).

As green bell peppers mature on the plant, their sugar content increases so they become sweeter (Sethu et al. 1996). They also develop higher nutrient content, primarily vitamins A and C (Howard et al. 2000; Luning et al. 1994; Márkus et al. 1999; Osuna-García et al. 1998; Simonne et al. 1997). The total soluble solids content of 'Domino' bell peppers increased rapidly from 6 to 8% during fruit maturation and ripening (Tadesse et al. 2002). Glucose and fructose contents increased significantly from the green to turning stage, and subsequently to the red stage, but the highest amount of sucrose was observed at the turning stage (Luning et al. 1994). Along with the changes in coloration, texture, and composition during ripening of bell peppers, sweetness, sourness, and red bell pepper aroma were reported to increase during ripening from the green to the red stage, whereas bitterness and grassy, green bell pepper, and cucumber aromas decreased significantly (Luning et al. 1994). Overall, the best quality green bell peppers should have firm flesh, bright skin color, and sweet flavor (González-Aguilar 2004).

Green bell peppers contain on average 92% water, 5% carbohydrates, 0.9% proteins, 2% fiber, 89 mg of vitamin C, and 632 IU of vitamin A per 100 g of fresh fruit (USDA 2006). Red fruit is in general much more nutritious than green fruit because it contains three times more vitamin C and four times more vitamin E than green fruit. Vitamin E (α-tocopherol) present in different pepper varieties increases during ripening, from the mature green to the fully red stages (Márkus et al. 1999; Osuna-García et al. 1998). Likewise, ascorbic acid levels increase during ripening and peak at the red stage. Consequently, ripe peppers have higher content of ascorbic acid than green peppers do (Howard et al. 2000; Luning et al. 1994; Márkus et al. 1999; Osuna-García et al.

1998; Simonne et al. 1997). Carotenoid content also increases as the peppers change from green to deep red (Hornero-Méndez and Mínguez-Mosquera 2000; Howard et al. 2000; Márkus et al. 1999; Simonne et al. 1997). A dramatic increase in the carotenoid content from 23.5-fold in 'Numex' to 38.0-fold in 'Nana' peppers was observed during ripening (Hornero-Mández and Mínguez-Mosquera 2000). Although colored peppers tend to have higher contents of vitamin C and carotenoids than green peppers do, green, red, and orange peppers were reported to have much higher contents of vitamin C and carotenoids than other unusually colored peppers such as black, purple, or white (Simonne et al. 1997).

Optimum Postharvest Handling Conditions

To avoid CI and to reduce water loss and shriveling, bell peppers should be pre-cooled using forced-air cooling with high relative humidity air as soon as possible after harvest to a temperature no lower than 7°C. Pre-cooling can also be accomplished using hydro-cooling or vacuum-cooling (González-Aguilar 2004). Chlorinated water treatments are sometimes used to remove field dirt and sanitize green bell peppers in order to make them more attractive in the market. However, the chlorine concentration and dipping time have a significant effect on the postharvest quality of the fruit. Green bell peppers dipped for more than 20 minutes in chlorine solutions with concentrations higher than 100 μg/mL followed by storage for 1 week at 10°C showed a decrease in chlorophyll, soluble solids, and ascorbic acid contents (Nunes and Emond 1999).

Storage of bell peppers at 7.5°C and 90–95% relative humidity is recommended for maximum postharvest life (i.e., 3–5 weeks) and to reduce water loss and shriveling. When stored at higher temperatures and lower relative humidity levels, peppers may lose water rapidly, becoming flaccid, shriveled, and dry (González-Aguilar 2004; Lownds et al. 1994). Because some cultivars may be susceptible to CI at 7°C, they should be stored at temperatures between 7 and 13°C. However, if stored at temperatures above 13°C, peppers may show accelerated ripening or senescence and decay. Green bell peppers can also be stored at 5°C for approximately 2 weeks, and although the low storage temperature reduces water loss, CI symptoms may begin to develop after that period. Symptoms of CI may develop after a few days at 0°C or a few weeks at 5°C. Ripe or colored peppers are less sensitive to CI than green peppers are (González-Aguilar 2004).

To delay ripening and compositional changes associated with ripening, reduce CI, and retard softening, the use of an adequate temperature can be supplemented by packaging the pepper in polymeric films (González and Tiznado 1993; González-Aguilar et al. 1999; Meir et al. 1995; Miller et al. 1986). If bell peppers are packed in a film with a low permeability to water vapor at a temperature between 7 and 10°C, their postharvest life can be extended by about a week (González-Aguilar 2004). However, excessive high levels of water vapor inside the package (i.e., 99–100% relative humidity) plus exposure to fluctuating temperatures during handling and distribution may lead to condensation inside the package and on the fruit surface, creating a favorable environment for pathogen development (Miller et al. 1986; Mohamed 1990; Rodov et al. 1995).

Temperature Effects on Quality

Water loss, tissue softening, shriveling, and CI are the principal factors that limit the quality and postharvest life of bell peppers (Hampshire et al. 1987; Kissinger et al. 2005; Lownds et al. 1994; Sethu et al. 1996; Smith et al. 2006). Because the bell pepper fruit is hollow, with a thin wall of approximately 5–8 mm thickness, it has a reduced capacity to store large volumes of water for long periods. Therefore, the fruit is easily subjected to loss of moisture and consequently to shriveling and loss of firmness (Kissinger et al. 2005). Moreover, poor postharvest handling practices may increase the fruit's susceptibility to water loss and quality deterioration. Ceponis et al. (1987) reported that 70% of the bell peppers that were inspected for conformity to grade standards upon reaching the New York market exhibited a variety of disorders. Softening, flaccidity, shriveling, and wilting as a result of water loss during postharvest handling combined with decay are the major problems that reduce postharvest marketability and consumer acceptance of bell peppers (Janse 1989).

Temperature during handling not only affects the texture of bell pepper fruit but also the rate of color development. Color developed faster when fruit was stored at 15.5°C compared with storage at 7°C (Miller et al. 1986). Bell pepper fruit harvested at different color stages from green to green-orange developed orange coloration after 10–15 days at 22°C. Conversely, the color of peppers stored at 7°C for 20 days did not change until the fruit was transferred to 22°C (González et al. 2005). Storage of green bell peppers at temperatures between 20 and 25°C led to the development of fully orange-red color (Meir et al. 1995). Red and yellow bell pepper varieties harvested at the onset of color change developed full-red or full-yellow color after approximately 5 days at 20°C (Molinari et al. 1999). Lownds et al. (1994) also reported that the rate of color changes in several different pepper cultivars was higher during storage at 14 or 20°C than at 8°C. Furthermore, the advanced color development at 14 or 20°C relative to 8°C paralleled differences in water loss rates and suggested a direct relationship between these variables. This relationship between changes in color and water loss should be considered to be cultivar and/or season dependent rather than assumed to be a generalization for all pepper cultivars. In fact, after 14 days of storage at 20°C, 'Bell Boy' peppers from a first harvest had higher rates of water loss (25%) and yellow color development than fruit from the second harvest of the same plants, which had only 5% water loss and were not completely yellow until after 20 days of storage (Nunes and Emond 2002).

The L* value (i.e., lightness) of 'Bell Boy' peppers showed a slight tendency to decrease throughout storage, although the changes were small. 'Bell Boy' green bell peppers stored at 20°C showed a significant increase in L* value after 20 days, reflecting the development of yellow coloration. The hue and chroma of bell pepper fruit stored at 0.5, 10, and 15°C did not change significantly during storage, in contrast to the hue and chroma of peppers stored at 20°C. Bell peppers stored at 20°C showed a hue angle of approximately 108 after 20 days, which corresponds to a yellowish color (a hue value of 90 degrees represents pure yellow). Although some of the peppers stored at 20°C showed a marked shift from green to yellow, other fruit remained green, even after 20 days at 20°C (Nunes and Emond 2002), probably reflecting variations in initial maturity.

Wrapping green bell peppers in plastic films may contribute to better green-color retention compared with nonwrapped fruit (González-Aguilar et al. 1999; Srinivasa et al. 2006). For example, the hue angle of green bell peppers packaged in different materials gradually decreased (became less green and more yellow) during storage, but showed the lowest value in unpackaged fruits (Srinivasa et al. 2006). Higher L* and hue values were reported for green bell pepper wrapped in a plastic film compared to nonwrapped fruit, meaning that wrapped fruit was more bright and green after 28 days at 8°C than nonwrapped fruit (González-Aguilar et al. 1999).

A detailed assessment of bell peppers in retail stores shows that very often the fruit feels soft, flaccid, and shriveled without tissue breakage. Peppers are often displayed without any kind of protective packaging and are thus subjected to adverse conditions, which may cause shriveling and increased softening as a result of loss of moisture. As peppers lose water they become less turgid and less firm (Showalter 1973). Losses in firmness of 19–21% were observed for fruit stored for 20 days at room temperature, whereas for fruit stored for the same period at 8°C, the loss in firmness was only 1–3% (Sethu et al. 1996). A pronounced increase in fruit softening was associated with increases in weight loss during storage for 12 days at approximately 15°C (Showalter 1973). A direct relationship was found between softening and water loss, as softening followed a pattern similar to that of water loss in peppers stored at 8, 14, or 20°C (Lownds et al. 1994). Although the firmness of 'Bell Boy' green bell peppers decreased for fruit stored at 0, 5, 10, or 15°C, softening never reached unacceptable levels. Conversely, the firmness of the peppers stored at 20°C attained unacceptable levels after approximately 5–18 days of storage, depending on the harvest date. The reason for the relatively low loss of firmness in 'Bell Boy' peppers stored at temperatures below 20°C may be related to the high relative humidity (90–95%) that was maintained during storage (Nunes and Emond 2002). In fact, when wrapped in a plastic film, green bell peppers stored for 28 days at 8°C maintained significantly greater firmness than nonwrapped fruit (González-Aguilar et al. 1999). Wrapped peppers stored for 4 weeks at 7 or 15.5°C and 90–95% relative humidity softened at a rate of –0.06 and –0.18 units per week, respectively, whereas the softening rate for nonwrapped fruit stored at the same temperatures was –0.17 and –0.38 units per week, respectively (Miller et al. 1986).

When exposed to temperatures lower than 7.5°C, green bell peppers may develop symptoms of CI such as pitting, water-soaked areas, decay, discoloration of the seed cavity, and softening without water loss (Cantwell 2006; González-Aguilar 2004). Symptoms of CI appeared as surface pitting followed by a combination of both surface and sheet pitting after 2–3 days at 0°C (Smith et al. 2006). Likewise, holding green bell peppers at temperatures in the range of 0–3°C for a 10-day period resulted in surface pitting and, subsequently, pathogen invasion (Burzo et al. 1994). Usually, symptoms of CI are aggravated when bell peppers are transferred to ambient temperature. Whitaker (1995) reported that approximately 30% of the 'Bell Tower' green bell peppers stored for 2 weeks at 2°C exhibited pitting on about 25% of their surface. Three days after return of the chilled fruit to 20°C, 60% showed severe pitting over about 30–40% of the surface. 'Bell Boy' peppers showed moderate signs of CI such as surface pitting and darkening of the seeds after approximately 13–14 days of storage at 0°C plus 1 day at 20°C and were considered unacceptable for sale. 'Bell Boy' green bell peppers stored at 5°C showed moderate signs of CI after approximately 17 days plus 1 additional day at 20°C (Nunes and Emond 2002). Green bell peppers stored at 1, 4, or 7°C for 14 days also developed CI symptoms such as pitting and seed discoloration after transfer to 15°C for 5 days (Miller and Risse 1986). 'Bell Boy' green bell peppers stored at 10, 15, or 20°C showed no CI symptoms during 14- or 20-day storage periods (Nunes and Emond 2002). Lin et al. (1993) reported that 'Bison' and 'Doria' mature-green peppers showed surface pitting after 3 days to 1 week at 1°C, but fruit stored at 13°C did not show any signs of CI symptoms.

Although a study by Miller and Risse (1986) showed that film-wrapping would not alleviate CI symptoms in green bell peppers stored at chilling temperatures, others have shown that storage of bell peppers in polyethylene bags for 14 days at 3°C or for 18 days at 1 or 4°C delayed the development and alleviated the symptoms of CI (Kosson 2003; Meir et al. 1995). Furthermore, wrapping in a plastic film may have delayed the development of CI symptoms in bell peppers stored for 28 days at 8°C compared to nonwrapped fruit (González-Aguilar et al. 1999, 2000). Mature-green peppers held at 4°C in perforated or nonperforated polyethylene bags did not develop CI symptoms on the fruit surface after 18 days. In contrast, peppers stored at 1°C plus 3 additional days at room temperature showed initial CI symptoms after 3, 6, and 9 days when stored without packaging, in nonperforated packaging, or in perforated packaging, respectively, with the peppers packaged in perforated polyethylene bags showing the lowest severity of CI (Kosson 2003). An increase in injury due to exposure to chilling temperatures generally corresponded with increased fruit water loss. A significant correlation was found between CI and percentage water loss for green bell peppers stored for 14 days at 0°C followed by 2 days at 20°C (Smith et al. 2006).

Softening, increased flabbiness, loss of turgidity, wilting and shriveling, and dryness are symptoms generally associated with loss of moisture. Lownds et al. (1994) reported that development of flaccidity in bell peppers appears to be directly associated with water loss. Hruschka (1977) observed that when extremely severe shrivel was noted in green bell peppers, percentage weight loss averaged 15% (ranging from 8 to 27%). Furthermore, deterioration in commercial appearance accompanied moderate shriveling symptoms and was noted when weight loss averaged 12% (ranging from 3 to 22%) (Hruschka 1977). According to Robinson et al. (1975), a weight loss of about 7% should be considered to be the maximum amount that is acceptable in terms of saleability. Lownds et al. (1994) reported that New Mexican type of peppers become flaccid in 3–5 days at 20°C, which corresponded to a weight loss of 7–10%. González and Tiznado (1993) also observed that when green bell peppers lose 5% of their initial weight, signs of shriveling become evident. Green and red bell peppers held for 3 weeks at 17°C and 85% relative humidity had a weight loss rate of 4% per week, which was accompanied by decreased firmness of the fruit. Decreasing the storage temperature from 17 to 8°C resulted in a reduction of about 50% in the rate of weight loss in green and red peppers. In peppers stored at 7°C, weight loss increased slightly from 0.39% after 1 week to 1.7% after 20 days (González et al. 2005). Weight loss of ‘Bell Boy’ peppers from two different harvests showed significant variation. Peppers from the first harvest stored at 20°C attained the maximum acceptable weight loss (i.e., 7%) after approximately 3 days of storage, whereas after 14 days, peppers stored at 0°C had a weight loss of 8%, which was similar to those stored at 10°C (9%). After 14 days of storage, peppers stored at 5°C still had an acceptable weight loss (5%), whereas after 14 days peppers stored at 20°C had approximately 25% weight loss. Conversely, in a second harvest, weight loss of ‘Bell Boy’ green peppers stored under the same storage conditions never reached the maximum acceptable weight loss of 7%, and after 14 days the fruit had only lost between 2 and 5% of its weight (Nunes and Emond 2002). In addition to decreasing the storage temperature to recommended levels, increasing the ambient humidity from 85% to a water-saturated atmosphere reduced the weight loss of green and red peppers by 90%, resulting in delayed senescence processes, better firmness retention, and inhibition of cell-wall breakdown (Lurie et al. 1986).

Water loss may be significantly reduced by packing bell peppers in plastic films (González and Tiznado 1993; González-Aguilar et al. 1999, 2000; Meir et al. 1995; Miller et al. 1986; Mohamed 1990; Srinivasa et al. 2006) or by using edible, mineral-based oil coatings (Lerdthanangkul and Krochta 1996). For example, water loss in film-wrapped green bell peppers stored for 14 or 28 days at 8°C was significantly lower (1.3 and 1.4%, respectively) than the weight loss of nonwrapped fruit (9.2 and 15.4%, respectively) (González-Aguilar et al. 1999, 2000). Wrapped peppers stored for 4 weeks at 7 or 15.5°C and 90–95% relative humidity lost weight at a rate of 0.06 and 0.12% per week, respectively, whereas nonwrapped fruit lost 0.74 and 1.29% per week, respectively (Miller et al. 1986); wrapping bell peppers provided a net reduction of 2.56% in weight loss, and no shriveling was observed. Compared to nonwrapped fruit, polyethylene bag packaging reduced weight loss by 40–50% for bell peppers stored for 2 weeks at 7.5°C followed by 3 additional days at 17°C (Meir et al. 1995). The weight loss in unpackaged bell peppers stored for 16 days at approximately 27°C was significantly higher (14–15%) compared with fruit packaged using different packaging materials. Bell peppers packed in a chitosan film lost 10–11% of their initial weight during 16 days at room temperature (27°C and 65% relative humidity), whereas fruit packaged in low-density polyethylene film lost 2–2.5% of its weight during the same period (Srinivasa et al. 2006). Bell peppers dipped in a solution of mineral-based oil and stored for 18 days at 10°C and 80–85% relative humidity lost less moisture than nontreated fruit. After 18 days, coated fruit had a weight loss of only 3.3% and was free from wilting and shriveling, whereas nontreated fruit had lost approximately 10% of its weight and showed severe wilting and shriveling (Lerdthanangkul and Krochta 1996).

The increase in water loss by bell peppers during storage may be associated with cellular breakdown, loss of membrane integrity, and removal of epicuticular waxes, which play an important role in water loss through the skin (González-Aguilar et al. 2000; Kissinger et al. 2005; Lownds et al. 1993). In addition, differences in water loss when different varieties of bell peppers are packed or maintained under the same storage conditions may suggest differences in cuticle thickness, the presence of pores and/or cracks, and epicuticular wax quality, which may vary from harvest to harvest (Lownds et al. 1994). The cuticle and its components (i.e., cuticle thickness, cuticular chemistry, and epicuticular wax chemistry and distribution) are the main barriers to water loss, and thus significantly affect the rate of water loss (Kissinger et al. 2005; Lownds et al. 1993; Smith et al. 2006). Water loss during storage of bell peppers at 8 or 20°C was significantly correlated with cultivar, initial water content, cell membrane ion leakage, lipoxygenase activity, ratio of surface area to volume, and amount of epicuticular wax (Kissinger et al. 2005; Lownds et al. 1993). Furthermore, membrane lipid content was lower in bell pepper genotypes that were more susceptible to water loss during storage, whereas peppers that had lower water loss maintained high levels of membrane lipid contents (Maalekuu et al. 2006).

Concurrently with changes in the sensory attributes of bell pepper fruit, compositional changes also take place and are greatly dependent on postharvest handling conditions. When bell pepper fruit was exposed to chilling temperatures in the range of 0–3°C, acidity increased by approximately

17% compared to storage at 10°C (Burzo et al. 1994). Likewise, fruit acidity increased during storage at 7°C but, after 35 days, acidity began to decrease (González et al. 2005). Ascorbic acid content of bell peppers did not show a significant change during 20 days at 7°C but decreased after 35 days (González et al. 2005). Total soluble solids concentration did not change substantially in green bell peppers stored in perforated polyethylene bags at 5 or 10°C for 28 days and did not differ according to the storage temperatures (Martinez et al. 2003). Titratable acidity in green bell peppers decreased by 75% between 14 and 28 days of storage at 8°C, whereas pH and total soluble solids did not change (González-Aguilar et al. 1999).

Time and Temperature Effects on the Visual Quality of 'Bell Boy' Green Bell Peppers

'Bell Boy' green bell peppers shown in Figures 5.18–5.28 were harvested fully developed, green, and firm from a commercial operation in the Orleans Island, Quebec, Canada, during the summer season (i.e., August–September). Promptly after harvest fresh peppers were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Changes in the visual quality of 'Bell Boy' green bell peppers are to a great extent dependent on the storage temperature. Major visual changes in peppers stored at temperatures lower than 10°C are attributed to CI, and they increase when the fruit is transferred to ambient temperatures. For fruit stored at temperatures above 5°C, major changes in the visual quality result from shriveling, darkening of the stem, or changes in fruit coloration. The color of 'Bell Boy' green bell peppers stored at 0, 5, 10, or 15°C changes from a bright green color to a more dull green color during storage (Figures 5.18, 5.21, 5.25, 5.26, and 5.27). However, some of the fruit, but not all, stored at 20°C shows a marked shift in color from green to yellow after approximately 10 days of storage. After 20 days, some of the peppers stored at 20°C are completely yellow (Figure 5.28).

Although 'Bell Boy' green bell peppers stored at 0°C maintain acceptable visual appearance for about 8–10 days (Figure 5.18), after just 2–4 days at this temperature small pits are visible, and after 12 days, CI symptoms render the fruit unacceptable for sale. When transferred to 20°C for 1 day, the symptoms of CI worsen; the pits increase in size and number and the seeds develop brownish coloration (Figures 5.19 and 5.20).

'Bell Boy' peppers stored at 5°C maintain acceptable visual appearance for approximately 16 days (Figure 5.21). However, after that period, development of CI limits the postharvest life of the peppers. After a 4-day exposure to 5°C, fruit transferred to 20°C for 1 day develops small pits on the skin. The symptoms of CI become more severe with increased exposure to 5°C, and the peppers show large pits, water-soaked areas, and browning of the seeds after 18 days at 5°C plus 1 day at 20°C (Figures 5.22 and 5.23). In some of the fruit the symptoms of CI are even more serious, as severe water-soaking of the tissues and complete fruit collapse become evident after 10 days of storage at 5°C followed by 1 day at 20°C. After 20 days at 5°C plus 1 day at 20°C, some fruit is also affected by decay that develops on the necrotic tissue in the pits caused by exposure to low temperature (Figure 5.24).

Visual quality of 'Bell Boy' peppers stored at 10°C remains acceptable for 14–16 days (Figure 5.25). Although after 14 days slight shriveling develops on the skin of the pepper, it does not increase further during the subsequent storage period. Darkening and dryness of the stem also become evident after 14 days.

'Bell Boy' green bell peppers stored at 15°C maintain acceptable visual appearance for 18 days (Figure 5.26). However, after 16 days, changes in the color, such as development of browning on the stem and slight surface yellowing, render the fruit unmarketable. At this temperature, other nonvisual quality factors also contribute to quality deterioration. Loss of firmness and development of an unpleasant aroma occurred after 18 days of storage.

Although 'Bell Boy' green bell peppers stored at 20°C maintain an acceptable visual appearance for 16 days (Figure 5.27), after 12 days detrimental changes in the color such as browning on the stems and slight skin shriveling develop. At this temperature, other nonvisual quality factors also contribute to quality deterioration. Loss of firmness and development of an unpleasant aroma occurred after 18 days of storage. Remarkable changes in the color of some 'Bell Boy' green peppers from green to fully yellow are observed between 12 and 20 days of storage at 20°C. However, the stem appears extremely dry and some brownish discoloration develops on the shoulder (Figure 5.28).

Overall, changes in fruit and stem coloration, skin shriveling, and symptoms of CI caused by exposure to cold temperatures, such as pitting, darkening of the seeds, water-soaking of the tissues, and decay are the most important visual factors that limit the postharvest life of 'Bell Boy' green bell peppers. Peppers stored at 10 or 15°C maintain good quality for longer periods (16–18 days, respectively) than peppers stored at either lower or higher temperatures. Peppers stored at 0, 5, or 20°C retain acceptable visual quality for 2, 4, and 12 days, respectively, but quality deteriorates very quickly afterward.

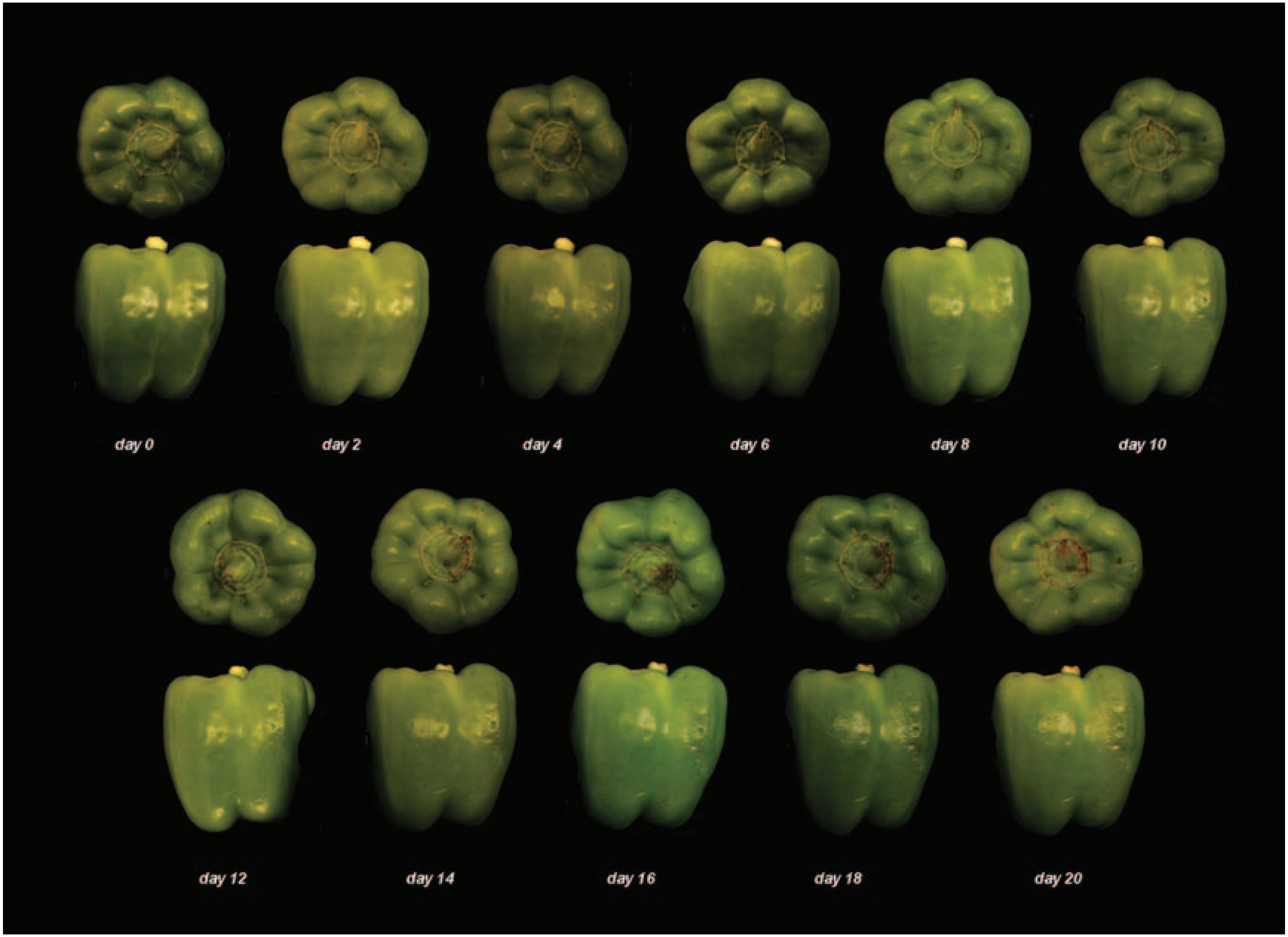
day 0
day 2
day 4
day 6
day 8
day 10
day 12
day 14
day 16
day 18
day 20

Figure 5.18. Appearance of ‘Bell Boy’ green bell peppers stored for 20 days at 0°C. Peppers maintain acceptable visual quality for 8–10 days at 0°C. After 10 days, slight pitting develops and, after 20 days, the pits increase in size and number. The stems dry up and develop a brownish-green color after 14 days at 0°C.

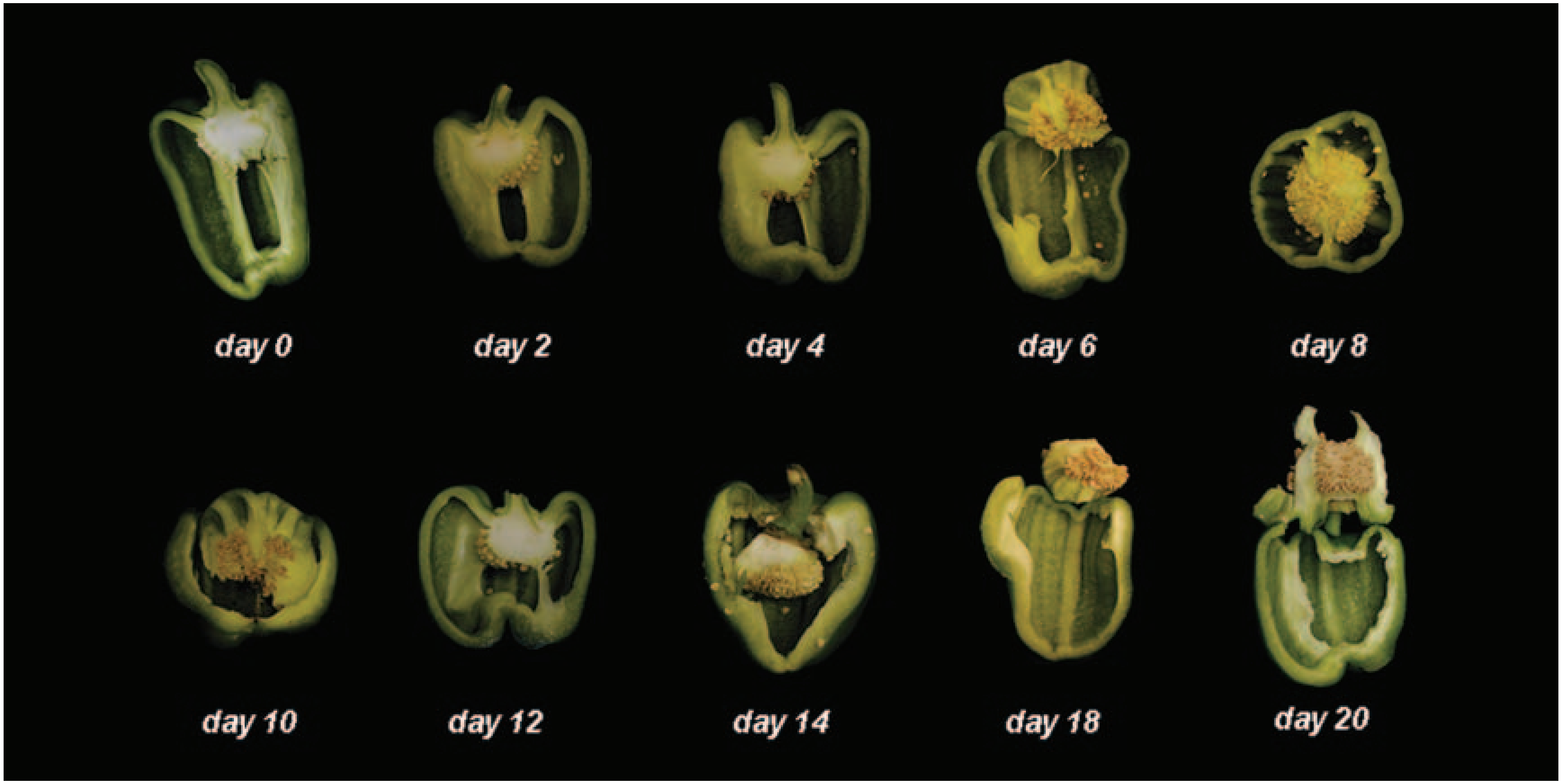
day 0
day 2
day 4
day 6
day 8
day 10
day 12
day 14
day 18
day 20

Figure 5.19. Darkening of the seeds increases in ‘Bell Boy’ green bell peppers stored for 20 days at 0°C followed by 1 day at 20°C. After 20 days, the seeds appear slightly darker than at the time of harvest.

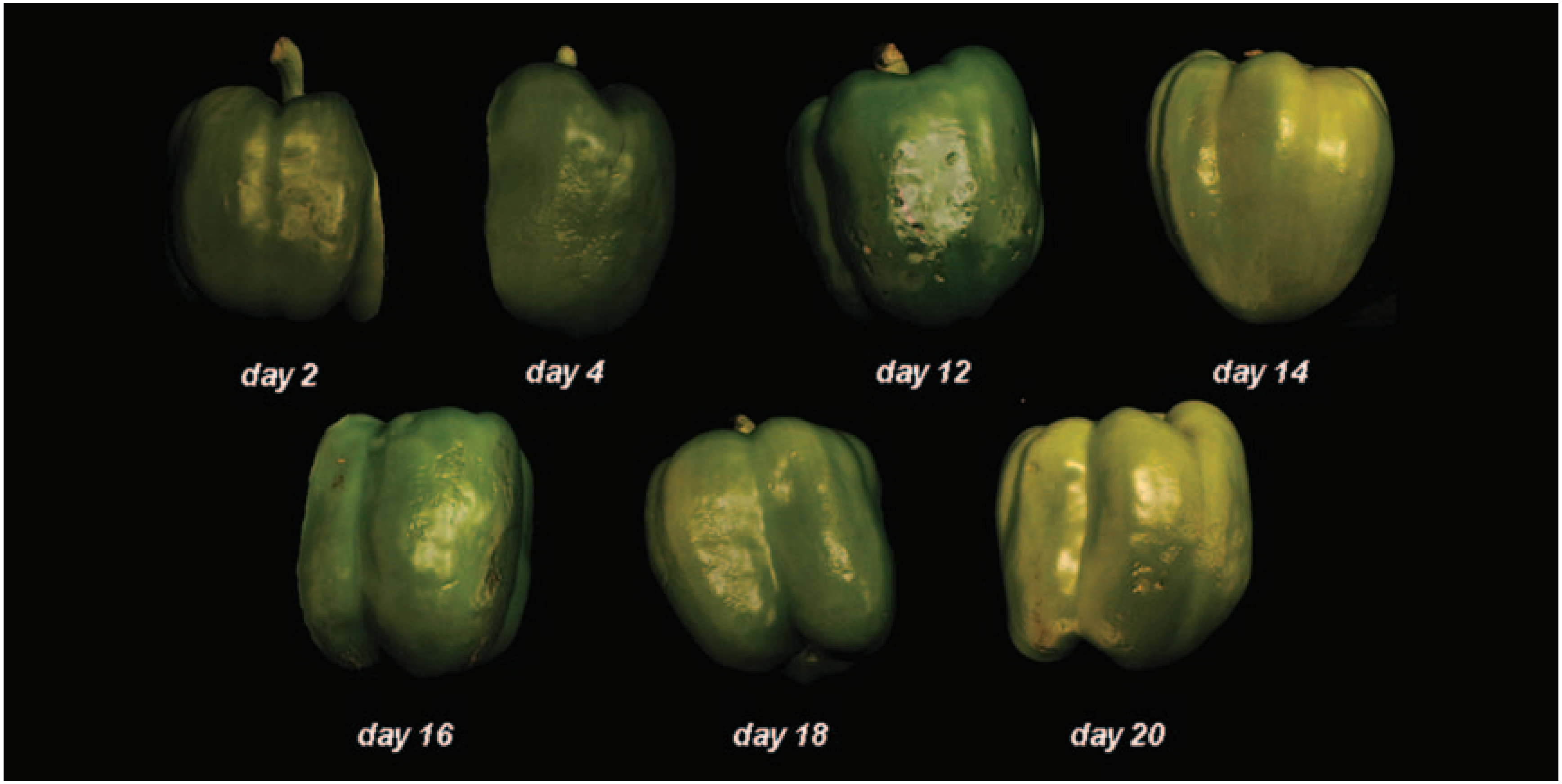
day 2
day 4
day 12
day 14
day 16
day 18
day 20

Figure 5.20. Surface pitting on 'Bell Boy' green bell peppers stored for 20 days at 0°C followed by 1 day at 20°C. After 2 days at 0°C, pitting of the skin becomes evident and, after 12 days, parts of the fruit surface are covered with small to large pits.

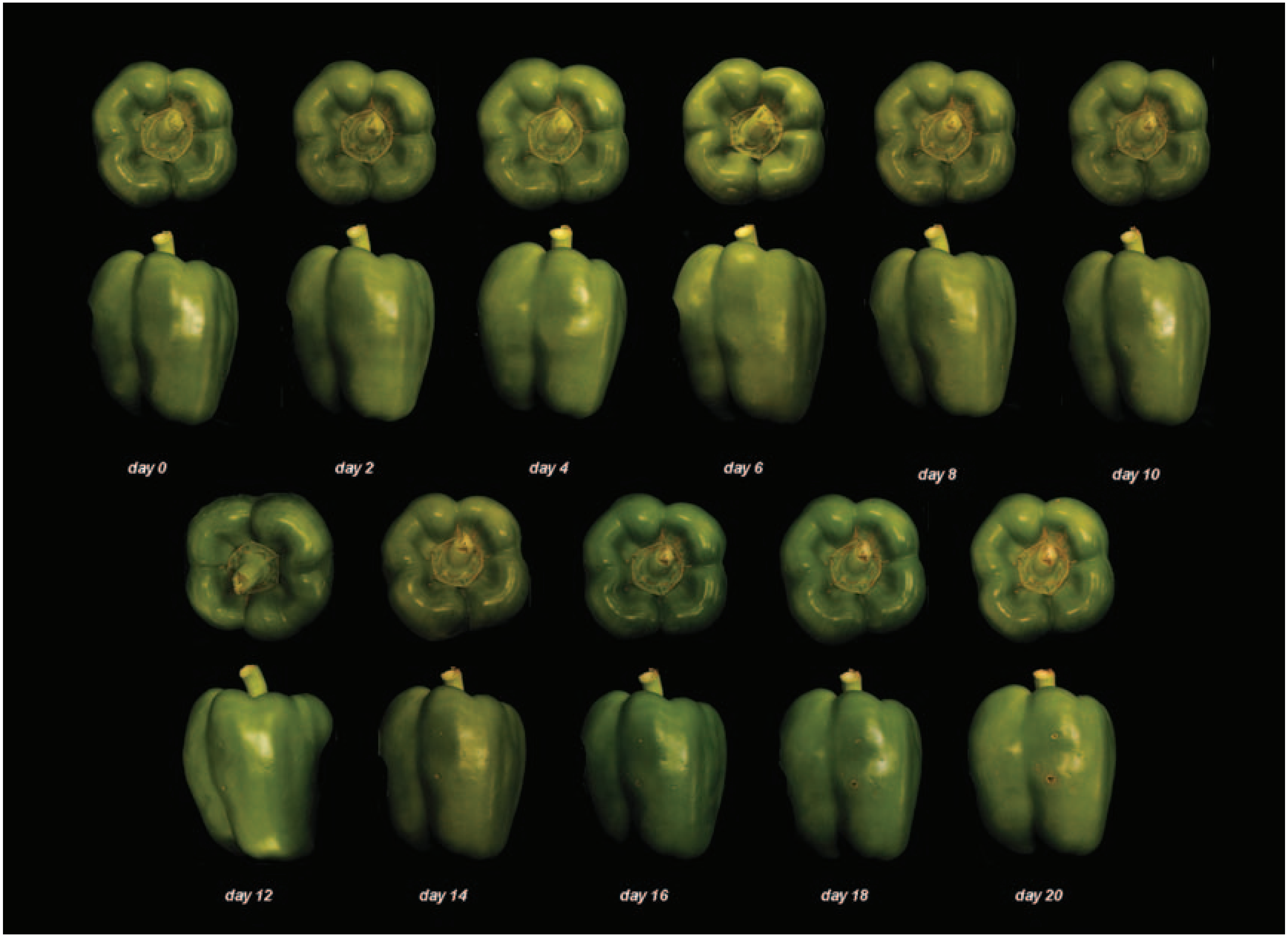
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Figure 5.21. Appearance of 'Bell Boy' green bell peppers stored for 20 days at 5°C. Peppers maintain acceptable visual quality for 16 days at 5°C. After 16 days, slight pitting develops and, after 20 days, the pits increase in size and the skin collapses. The stems dry up and develop a brownish-green color after 14 days at 5°C.

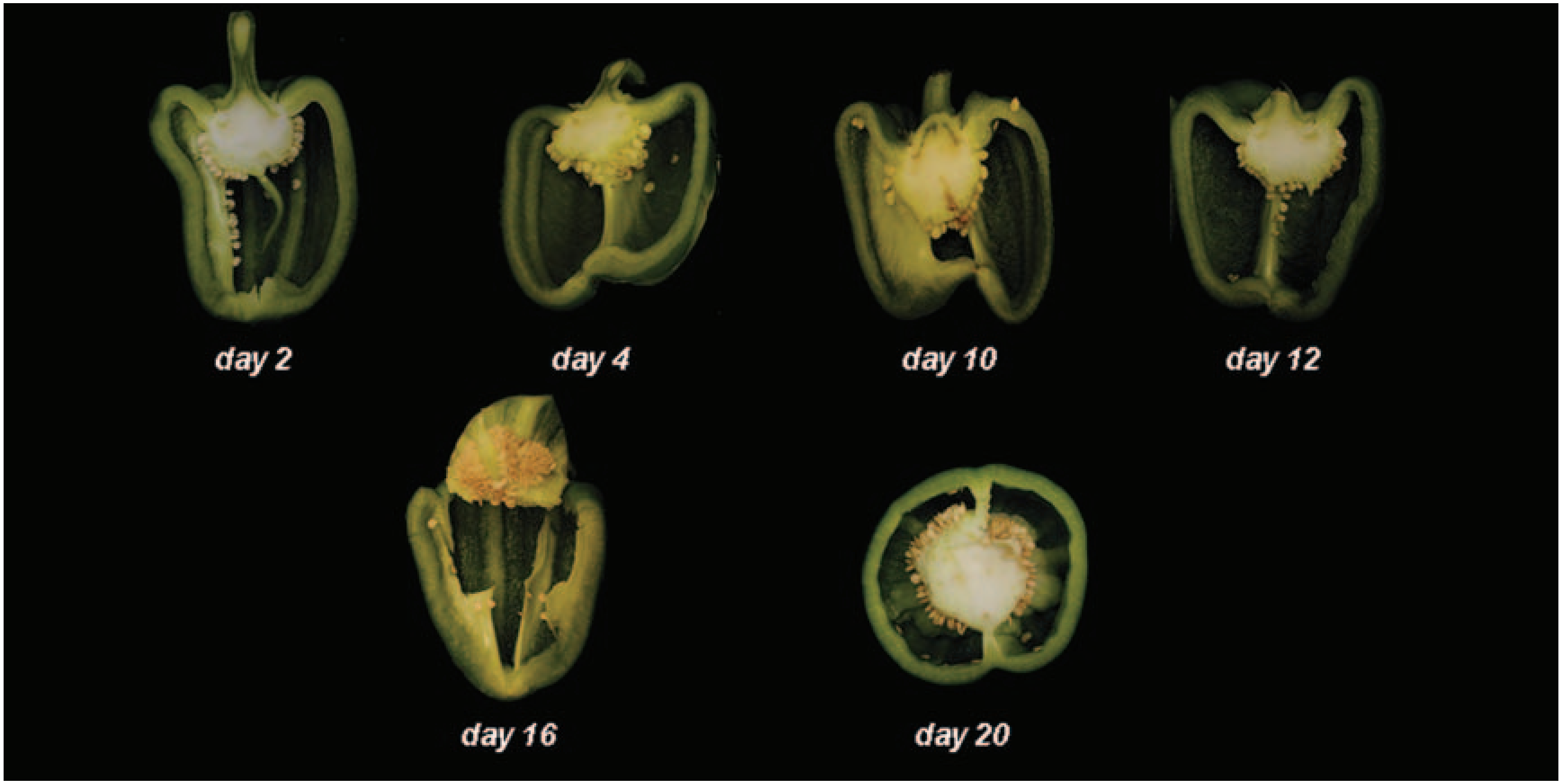
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Figure 5.22. Darkening of seeds increases in ‘Bell Boy’ green bell peppers stored for 20 days at 5°C followed by 1 day at 20°C. After 20 days at 5°C, the seeds appear slightly darker than at the time of harvest.

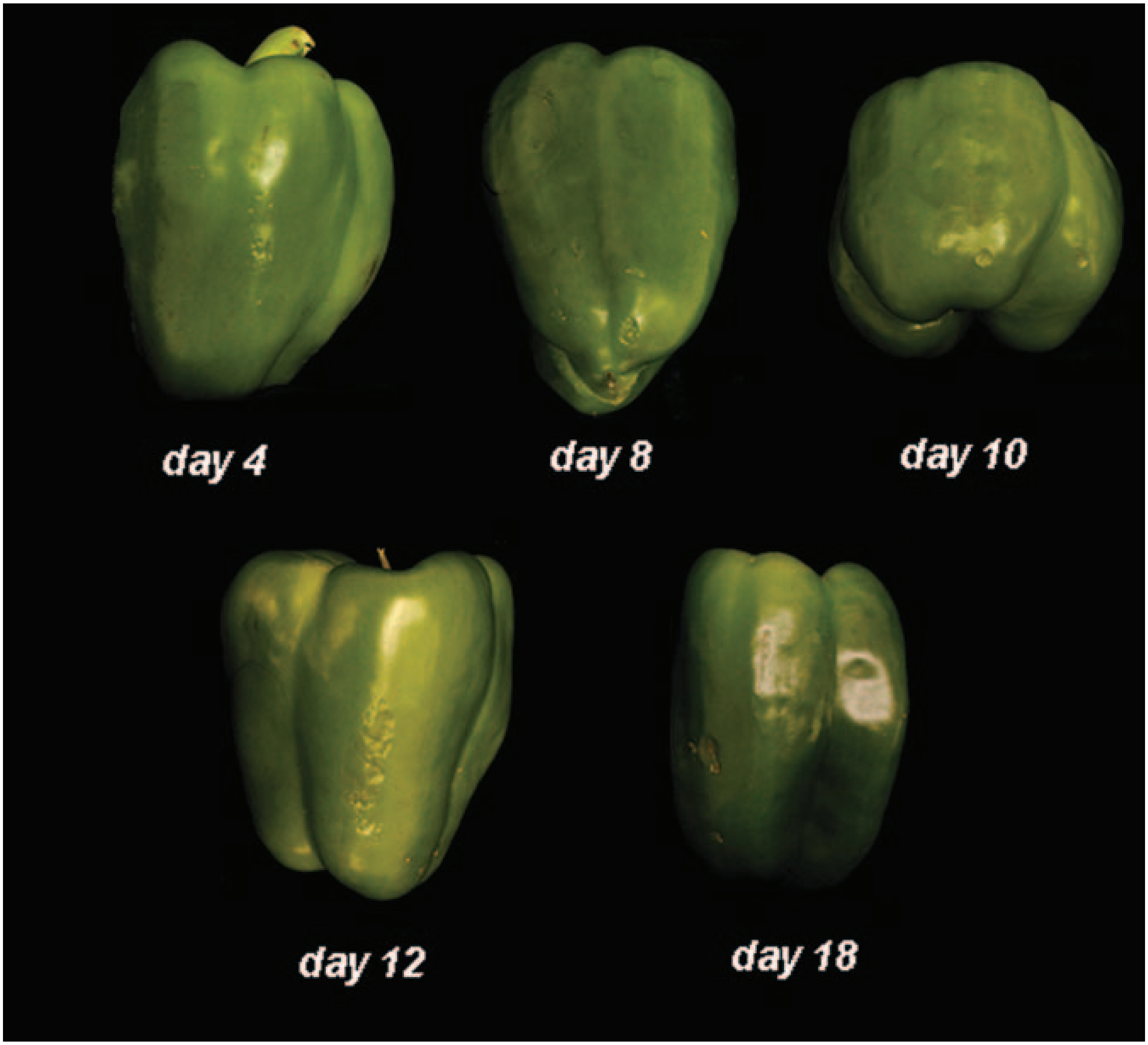

Figure 5.23. Surface pitting on 'Bell Boy' green bell peppers stored for 20 days at 5°C followed by 1 day at 20°C. After 4 days at 5°C, small pits become evident on the fruit surface and, after 12 days, parts of the fruit surface are covered with small to large pits.

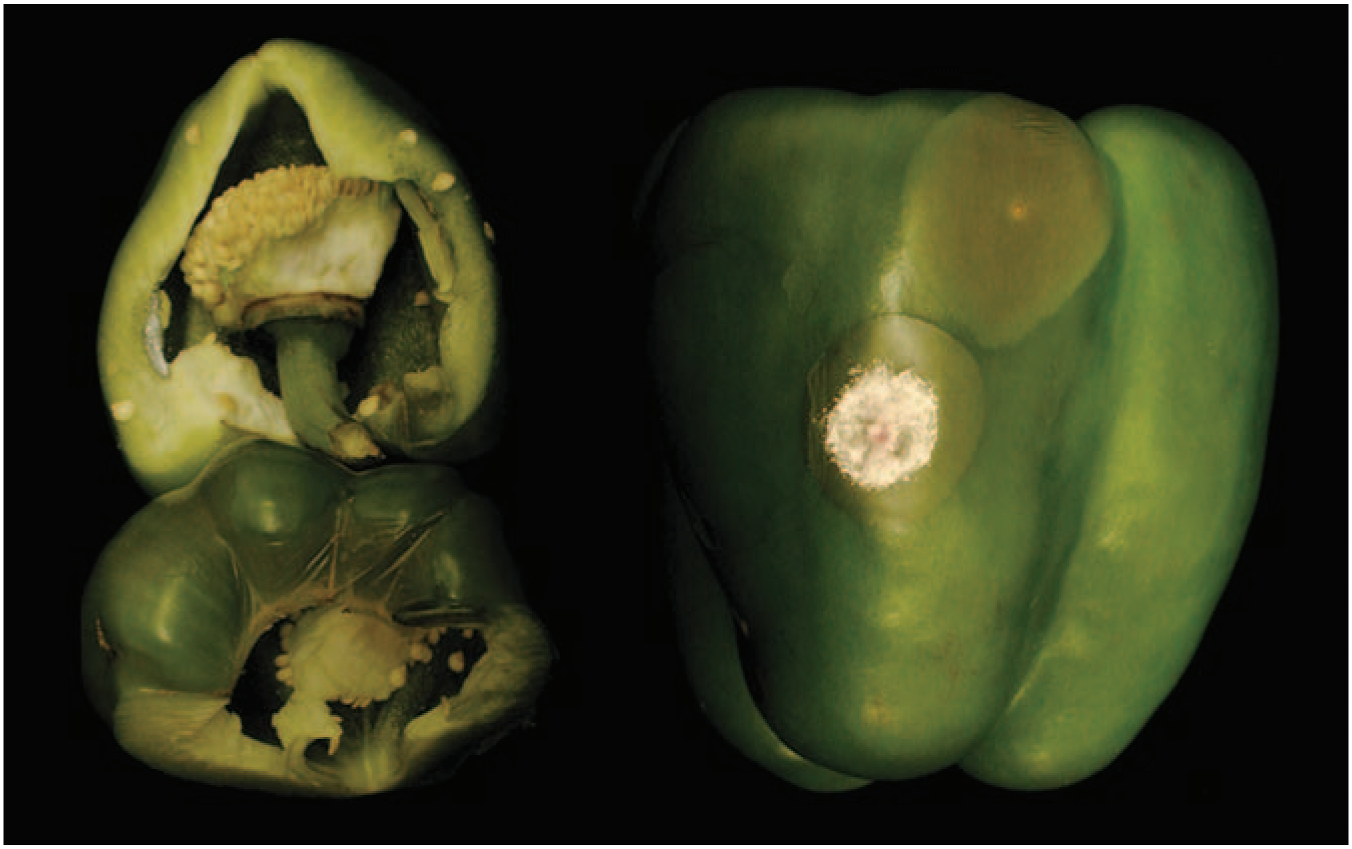

Figure 5.24. Water-soaking and decay of 'Bell Boy' green bell peppers stored for 10 days (left) and 20 days (right) at 5°C followed by 1 day at 20°C.

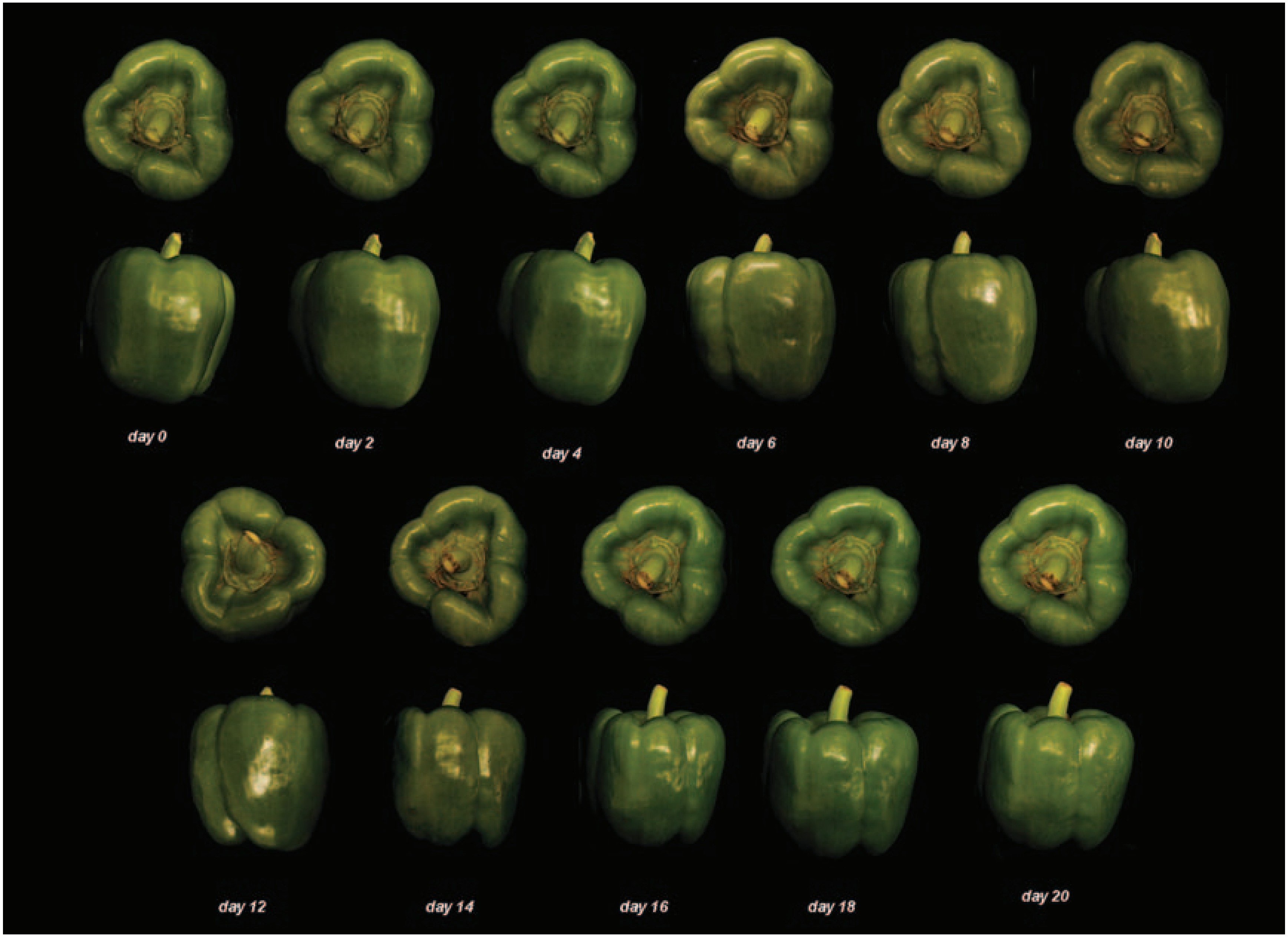
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Figure 5.25. Appearance of ‘Bell Boy’ green bell peppers stored for 20 days at 10°C. Peppers maintain acceptable visual quality for 14–16 days at 10°C. After 14 days, shriveling of the skin and darkening of the stem are evident.

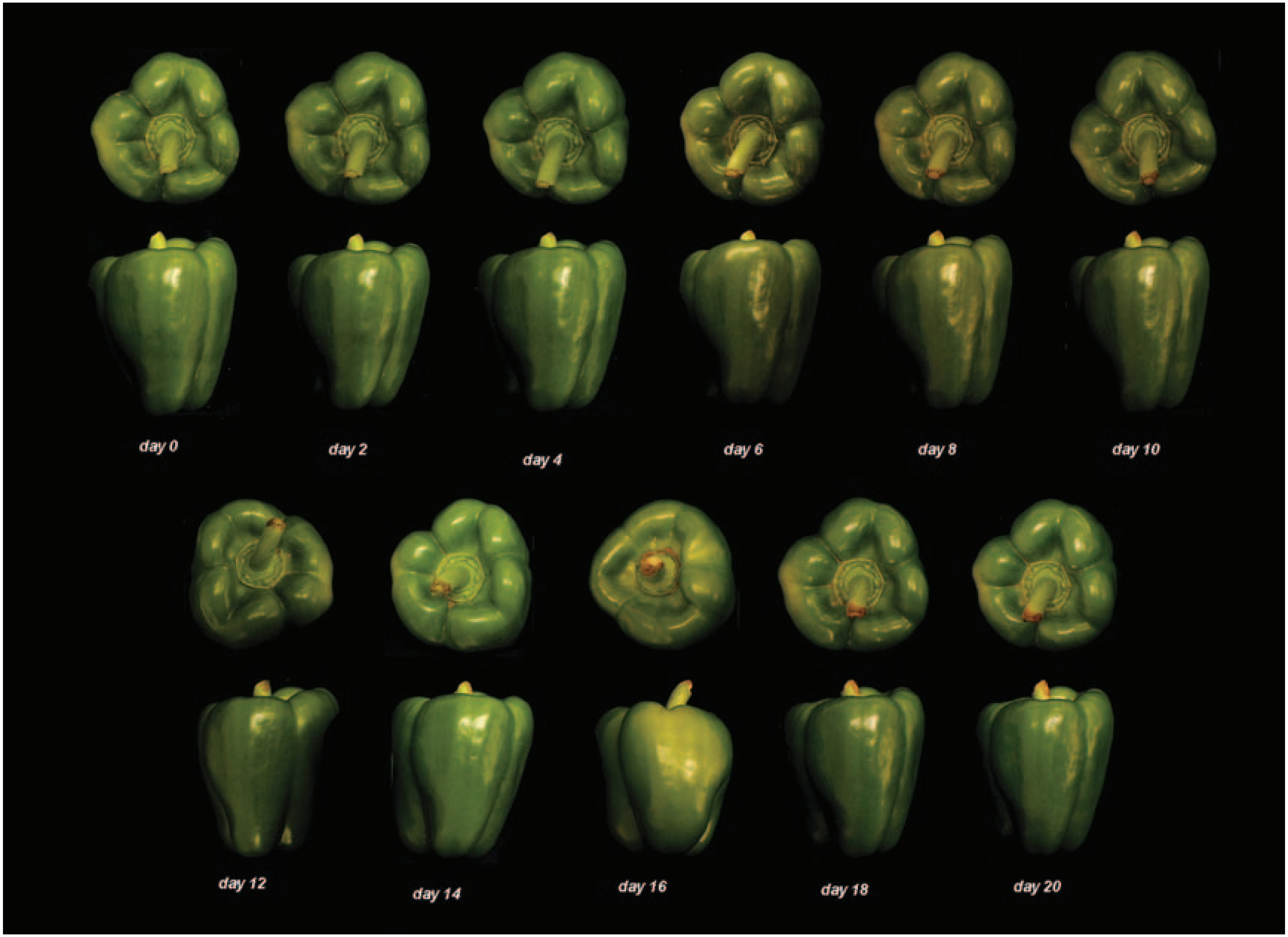
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Figure 5.26. Appearance of 'Bell Boy' green bell peppers stored for 20 days at 15°C. Peppers maintain acceptable visual quality for 18 days at 15°C. After 16 days, shriveling of the skin and darkening of the stem are evident, while some yellowing develops on fruit surfaces.

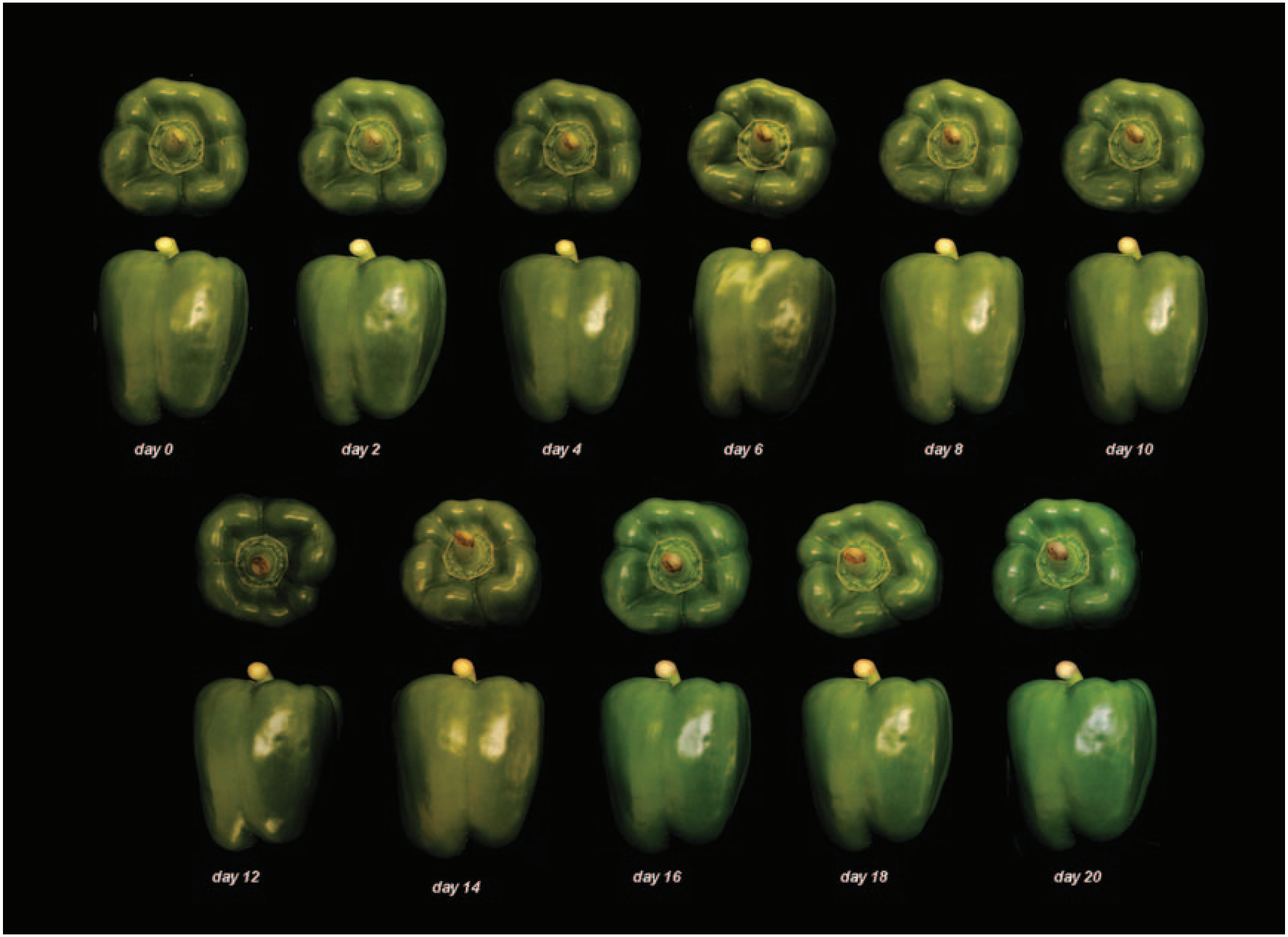
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Figure 5.27. Appearance of 'Bell Boy' green bell peppers stored for 20 days at 20°C. Peppers maintain acceptable visual quality for 16 days at 20°C. After 12 days, slight shriveling of the skin and darkening of the stem become evident.

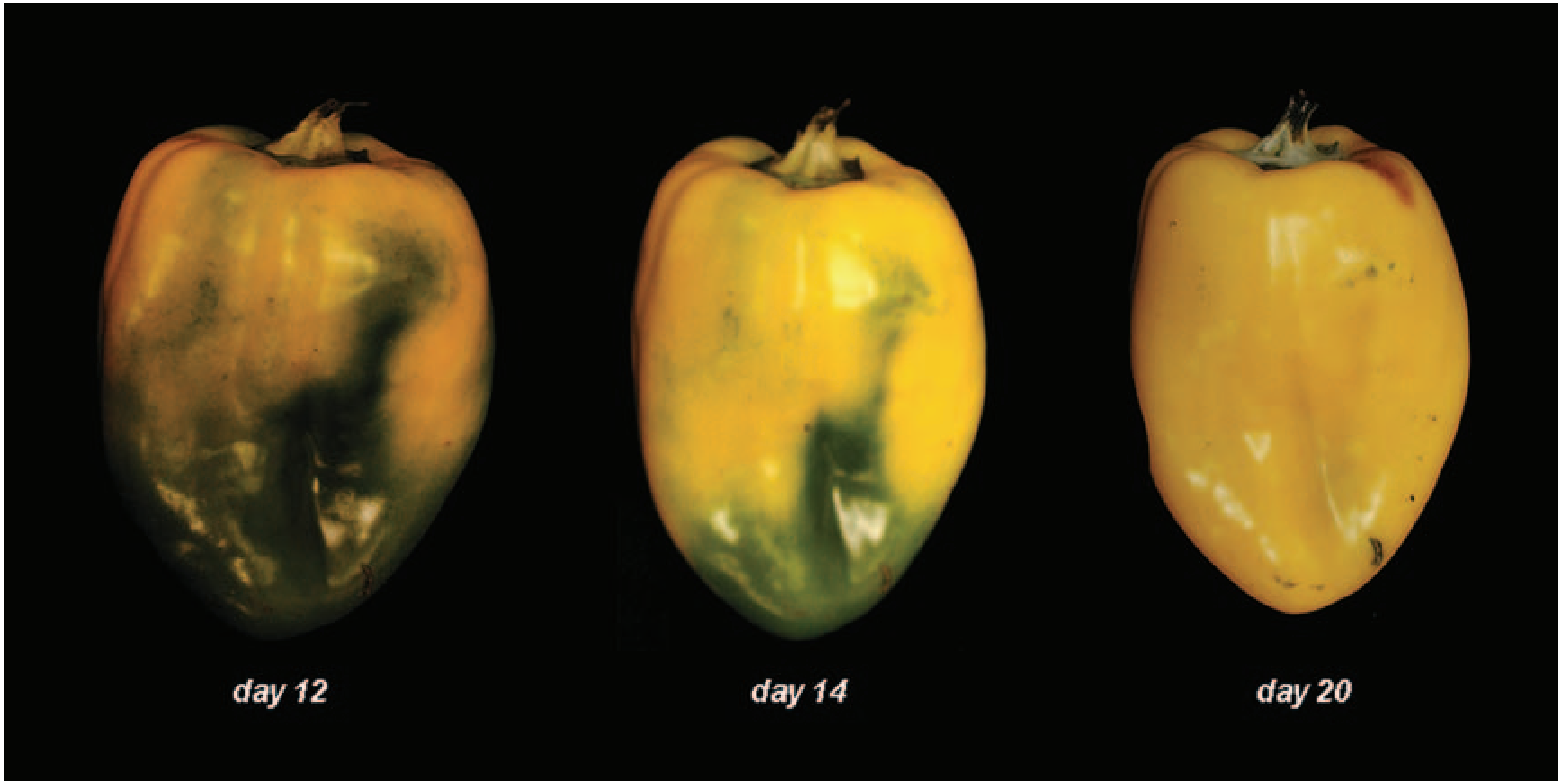

Figure 5.28. Color development of 'Bell Boy' green bell peppers stored for 20 days at 20°C. After 12 days, the color of the fruit changes from green to yellow and, after 20 days, the fruit is completely yellow. The stems appear extremely dry and some brownish discoloration develops on the shoulders.

EGGPLANT

Scientific Name: *Solanum melongena* L.
Family: Solanaceae

Quality Characteristics

Eggplant is a warm-season plant that, depending on the cultivar, produces fruit with many different shapes and colors. Eggplant fruit may be creamy-white, small, and egg-shaped to globular, or may be light to dark purple, elongated, and slim like the Japanese eggplants, or green, small, and grape-like like the Thai eggplants. Some other eggplant cultivars are rosy pink-and-white striped or purple-and-white striped. However, the most common eggplant cultivar is a large egg-shaped to globular fruit with a smooth, glossy, dark purple skin (Nothmann 1986; Sargent 1998; Siller-Cepeda 2004).

Eggplant fruit is harvested by hand at a physiologically immature stage when the seeds are still soft and small. Best quality eggplants should have tender skin, firm and not spongy flesh, succulent seeds, a fresh green calyx, and glossy skin with color that is characteristic of the cultivar (Cantwell and Suslow 2007; Flick et al. 1977; Sargent 1998; Siller-Cepeda 2004). As eggplants mature, the flesh becomes softer and spongy, the skin develops areas of unusual color, and the seeds become larger and harder. Overmature eggplants are pithy and bitter and feel soft to finger pressure (Sargent 1998).

During eggplant development, the pH of the flesh initially increases (between days 5 and 15 after fruit set) but declines rapidly afterward. At harvest maturity, the pH of eggplant fruit may range from 4 to 5.9 (Aubert 1971; Esteban et al. 1992). Changes in fruit acidity parallel in an inverse manner those in pH, decreasing sharply in the first stages of development and increasing slightly thereafter. Total sugar content of eggplants increases during development from 0.88 g to a maximum of 1.25–5.0 g per 100 g fresh tissue weight (Aubert 1971; Rodriguez et al. 1999). After 6 weeks from fruit set, total sugar content attains its maximum level, and fruits reach their optimum sensory quality. After that, sugar content decreases, reducing the fruit's eating quality (Esteban et al. 1992). Glucose, fructose, sucrose, and maltose are the major sugars in eggplants, but glucose and fructose concentrations are six times higher than sucrose and maltose levels. During fruit growth, glucose and fructose contents increase by 60 and 40%, respectively, although sucrose and maltose contents remain almost constant throughout the ripening period (Kozukue et al. 1978; Rodriguez et al. 1999).

The ascorbic acid content of eggplants increased during fruit growth until 42 days after fruit set, decreasing thereafter (Esteban et al. 1992). Likewise, total phenols increased during fruit development until day 42 and declined afterward. The increases in ascorbic acid and total phenolic contents of three different eggplant cultivars (semi-round striped, purple long, and black round) were coincident with the increase in total sugar content and, after 42 days from fruit set, the fruit was considered to be at its maximum of visual and eating quality (Esteban et al. 1992).

The dark purple coloration of the epidermis of eggplant fruit is attributed to the relatively high concentration of anthocyanin pigments, which consist mainly of delphinidin derivates (Nothmann 1986; Sakamura and Obata 1963). Accumulation of anthocyanin pigments starts at the fruit apex, spreading gradually toward the base of the fruit (Nothmann 1986). Maximum anthocyanin concentrations were observed in dark-colored fruit, with a gradual decrease with declining intensity of purple color. The highest concentrations of anthocyanins were accompanied by the highest chlorophyll levels. Dark purple fruit contained more chlorophyll than dark green fruit, but dark green eggplants contained twice the amount of chlorophyll as light green fruit. White eggplants contained almost no pigments (Nothmann et al. 1976).

Darkening and discoloration of the flesh is rapid in eggplants that have been subjected to rough handling that results in breaks in the epidermis, and has been attributed to the enzyme polyphenol oxidase (PPO). The enzyme activity was reported to be highest in purple eggplants, less in green eggplants, and lowest in white eggplants (Flick et al. 1977), most likely due to the higher concentration of phenolic compounds in purple eggplants compared with those of the green or white varieties (Nothmann et al. 1976).

Depending on the cultivar and environmental conditions during development in the field and during the postharvest period, eggplants may contain on average 90.3–94.2% water, 5.7% carbohydrates, 1.0% proteins, 3.4% fiber, and 2.35% total sugars. Eggplant is a poor source of β-carotene and vitamin E, with average values of 16 μg per 100 g fresh weight and 0.30 mg per 100 g fresh weight, respectively. Compared with other fruits, eggplants contain small amounts of vitamin C, ranging from 1.5 to 4.7 mg per 100 g fresh weight (Aubert 1971; Flick et al. 1977; Floyd and Fraps

1939; USDA 2006). However, purple eggplants are a good source of phenolic compounds and, at harvest maturity, the total phenolic content of eggplants may range from 345 to 7,896 µmol per 100 g tissue dry weight, depending on the cultivar (Hanson et al. 2006; Stommel and Whitaker 2003).

Optimum Postharvest Handling Conditions

Eggplants should be promptly cooled to 10°C after harvest to retard skin discoloration, weight loss, drying of the calyx, and decay. Although hydro-cooling and forced-air cooling are most effective, room-cooling is most commonly used to remove field heat (Siller-Cepeda 2004). Following precooling, eggplants should be stored at temperatures between 10 and 12°C with 90–95% relative humidity (Cantwell and Suslow 2007; Sargent 1998). Under such conditions, the postharvest life of eggplants is expected to be 10–14 days (Kaynas et al. 1995; Sargent 1998; Tătaru and Hristea 1977). Storage of eggplants at temperatures lower than 10°C results in CI, whereas storage at nonchilling temperatures results in rapid deterioration owing to loss of sheen and shriveling. Therefore, eggplant fruit is not well adapted to long-term storage and should be consumed within 1–2 weeks after harvest (Sargent 1998).

Temperature Effects on Quality

Eggplants inspected by the USDA at the New York market for conformity to grade standards in the 1980s had brown discoloration (i.e., scald), sunken discoloration, and pitting as the major damaging disorders associated with CI, following fruit rot and shriveling, which are, in general, associated with exposure to higher than recommended temperatures (Ceponis et al. 1988). In fact, eggplants are very susceptible to low temperatures and may develop CI when stored below 10°C. The severity and intensity of the symptoms increase as the temperature decreases or with increased exposure times and after removal from the chilling temperature. The most common symptoms of CI in eggplant are surface pitting, scalding or surface bronzing, and browning of the seeds and flesh. Scald is characterized by brown spots or shallow areas on the fruit surface, which usually become sunken with increasing exposure time to chilling temperatures (Sargent 1998; Siller-Cepeda 2004).

Sensitivity to CI is also dependent on the cultivar, maturity, size of the fruit, and season of harvest. In general, smaller and less mature fruit is more sensitive to CI than larger and more mature fruit. In addition, fruit harvested in mid-summer is more sensitive to CI than that harvested in the fall (Fallik et al. 1995; Sargent 1998).

American eggplants are in general more susceptible to CI than Japanese eggplants, which in turn are more susceptible than Chinese cultivars (Molinar et al. 1996). For example, American eggplants develop visual symptoms of CI after 1–2 days at 0°C, whereas for Japanese eggplants the symptoms develop after 2–3 days at 0°C. When stored at 5°C, American eggplants develop CI symptoms after 6–7 days, whereas Japanese and Chinese eggplants may remain free from CI for up to 9 or 12 days at 5°C, respectively (Siller-Cepeda 2004). Japanese eggplants stored at 1°C developed the first signs of browning after 2 days of storage (Kozukue et al. 1979).

The most obvious evidence of CI in ‘Classic’ eggplants stored at 6 or 8°C was the appearance of surface pitting on the calyx and on the epidermis and development of internal browning after 2–10 days of storage, upon transfer of the fruit to 17°C for 3 additional days (Fallik et al. 1995). Exposure of eggplants to temperatures between 0 and 3°C for a 10-day period resulted in surface pitting and depressions. The epidermal and hypodermal cells in these damaged areas were completely altered, with the plasmalemma and tonoplast broken and the cellular content electrondeusified. Those lesions were subsequently invaded by decay organisms (Burzo et al. 1994). The visual appearance of ‘Money Maker’ eggplants stored at 0°C changed after 2 days of storage, when the fruit exhibited slight skin discoloration and loss of brightness, particularly on the skin under the calyx, where color turned from purple to light purple. After 6 days, CI symptoms such as surface pitting and slight browning of the seeds became evident and, after 8–9 days, surface scald and browning of the pulp tissue rendered the fruit unacceptable for sale. After 15 days at 0°C, severe cellular disruption was observed, and CI symptoms intensified further when the fruit was transferred to 20°C for 24 hours (Concellón et al. 2004, 2005, 2007). Flesh of ‘Black Oval’ and ‘Black Magic’ eggplants stored at 2°C became spongy during storage, and after 7 days browning was also noticeable (Sistrunk and Buescher 1975). ‘Black Nite’ eggplants stored at 3°C showed initial symptoms of CI after 3 days, manifested by the development of pitting on the fruit surface; after 6 days, flesh browning and seed darkening became apparent (Rodriguez et al. 2001). Eggplants stored at 5°C showed the first signs of CI, such as discoloration of the epidermis, after 2 days, and loss of brightness after 5 days; after 8 days, initial pitting and slight browning of the seeds were noticed, whereas after 12 days at 5°C initial browning of the pulp tissue with slight scalding was evident (Concellón et al. 2004). Scalding, pitting, and darkening of the pulp and seeds were also observed in eggplants stored at either 6 or 8°C for 14 days followed by 2 additional days at ambient temperature (Brackmann et al. 1998).

The CI threshold temperature of 10°C is well established by numerous observations that eggplant fruit stored at 10°C for a period of 10–17 days did not show any CI-related physiological disorders or degradation of cell structure during storage (Brackmann et al. 1998; Burzo et al. 1994; Concellón et al. 2004, 2005, 2007; Molinar et al. 1996; Sistrunk and Buescher 1975). Although ‘Black Bell’ and Japanese eggplants stored at 10 or 12.5°C did not show any visual signs of CI during a storage period of 21 days, high levels of decay, especially on the calyx, were observed (Molinar et al. 1996). The calyces of 92% of eggplant fruit stored for 14 days at 12°C followed by 4 additional days at

20°C were completely dry and covered with heavy mycelium mats after storage (Temkin-Gorodeiski et al. 1993).

Turgidity, glossiness, and firmness of eggplant fruit depend mainly on loss of moisture during storage and are greatly influenced by the storage temperature. During storage, loss of glossiness is highly correlated with increases in weight loss and softening and is exacerbated as temperature increases (Jha and Matsuoka 2002a, 2002b; Jha et al. 2002). The eggplant calyx is considered the main pathway for fruit weight loss and accounts for at least 60% of fruit transpiration (Díaz-Pérez 1998).

Eggplants are very susceptible to water loss, and symptoms may become apparent when weight loss reaches 3% (Sargent 1998). When weight loss reached 8% of the initial fruit weight, eggplants were considered unacceptable for sale (Tàtaru and Hristea 1977). Turgidity and firmness decreased when weight loss reached 4–5% and, depending on the cultivar, such changes occurred after 4–5 days at 20°C or 8–12 days at 10°C (Tàtaru and Hristea 1977). After 12 days at 5 or 10°C, eggplant fruit had lost 8.8 and 10.4% of its initial weight, respectively, and the fruit appeared shriveled and soft (Mencarelli et al. 1989). Weight loss in eggplants stored at 12°C also increased during storage, attaining approximately 12% after 14 days and 20% after 42 days (Kaynas et al. 1995). In another study, weight loss in eggplants stored at 12°C attained 14% of the initial fruit weight after 10 days, and at this time the fruit was softer and less shiny than at the time of harvest (Moretti and Pineli 2005). After 14 days, the quality of the fruit was still considered acceptable, but after 28 days, when weight loss was higher than 15%, eggplant quality was considered poor (Kaynas et al. 1995). After 6 days at 20°C, 'Black Nite' eggplants were considered unacceptable for sale owing to accelerated fruit senescence (Rodriguez et al. 2001).

Protective plastic film has been successfully used to alleviate or delay the development of CI, while reducing weight loss, fruit softening, and overall deterioration. However, in some cases, it may enhance the development of decay. Eggplants stored for 1–3 weeks at 7–8°C in nonperforated film showed no signs of CI compared to nonwrapped fruit or fruit wrapped in paper tissue or perforated film (Fallik et al. 1995). Eggplant fruit wrapped in nonperforated plastic films and stored for 12 days at 5 or 10°C lost less weight (0.2–1.3% weight loss), was firmer, and had higher ascorbic acid content compared with unwrapped samples or those wrapped in perforated plastic film (7.6–10.4% weight loss) (Mencarelli et al. 1989). Likewise, bulk eggplant packed in nonperforated polyethylene bags and stored for 14 days at 12°C lost less weight (0.7%) and was significantly firmer than fruit packed individually or wrapped in perforated lining (1.5% weight loss) (Fallik et al. 1994). Nevertheless, development of decay during storage may be a problem for eggplants wrapped in plastic films (Fallik et al. 1994; Risse and Miller 1983). For example, decay increased in all eggplants, particularly in fruit wrapped in nonperforated film, during storage for 1 week at 7°C plus 7 days at 16°C, or for 2 weeks at 7°C plus 3 days at 16°C, or 3 weeks at 7°C (Risse and Miller 1983).

Parallel to changes in the visual quality of eggplant fruit, compositional changes also occur and are influenced significantly by postharvest handling temperatures. For example, the acidity of the cellular sap in eggplants exposed to temperatures between 0 and 3°C for 10 days was maintained significantly higher than in fruit stored at 10°C. In eggplants exposed to chilling temperatures, acidity values increased by 17.3% after a 10-day storage period compared with initial values (Burzo et al. 1994). In eggplants stored at 1°C, malic acid concentration decreased slightly after 2 days, and then increased after 10 days of storage. After transfer of the fruit from 1 to 20°C, malic acid content increased markedly, whereas citric acid decreased slightly. The malic-to-citric acid ratio in fruit stored at 1°C decreased during storage, whereas it increased in fruit stored continuously at 20°C (Kozukue et al. 1978). In eggplants stored for 2 days at 1°C, the initial fructose content of the fruit increased by 62%, decreasing gradually thereafter. Likewise, the total sugar content of fruit stored at 1°C increased by 20% after 2 days, decreasing sharply afterward. However, after transfer of the fruit from 1 to 20°C, fructose, glucose, and maltose contents increased rapidly (Kozukue et al. 1978).

Acidity and total sugar, starch, and ascorbic acid contents decreased, whereas soluble solids content increased in eggplants stored at 12°C (Kaynas et al. 1995). Esteban et al. (1989) reported an increase in the acidity of eggplants with increasing storage temperature, whereas total sugar content decreased after approximately 15 days at 10 or 20°C. In eggplants stored at 20°C, total sugar, fructose, glucose, and maltose contents decreased gradually during a 10-day storage period (Kozukue et al. 1978). A remarkable decrease in sugar content of eggplants was observed during simulated shipping conditions from the harvest point to the market (46%) compared to continuous storage at 10°C (9%) (Nei et al. 2005).

Ascorbic acid content of eggplants reportedly decreased by 75% after 18 days of storage at 10 or 20°C, but at 5°C the reduction was less pronounced (Esteban et al. 1989). After 14 days at 10 or 12°C, ascorbic acid content of eggplant fruit was reduced by approximately 43 and 58%, respectively (Arvanitoyannis et al. 2005; Kaynas et al. 1995).

Chlorogenic acid, the main phenolic compound identified in Japanese eggplants, decreased during storage for 2 days at 1°C, increased rapidly after 4 days, and decreased gradually thereafter. For eggplants stored for 2 days at 1°C plus 30 hours at 20°C, chlorogenic acid content increased gradually during the 30 hours after removal of the fruit from cold storage. Likewise, chlorogenic acid content increased steadily during a 10-day storage period at 20°C (Kozukue et al. 1979). Esteban et al. (1989) reported an initial increase in the polyphenol content of eggplants stored at 10 or 20°C, with an even greater increase observed at 5°C. The increased development of browning of eggplant fruit during storage was attributed to the rapid increase in chlorogenic acid, as the oxidative substrate, after 4 days of storage at 1°C and during storage at 20°C (Kozukue et al. 1979).

The anthocyanin content of eggplants decreased by 56% during the first 6 days of storage at 10°C and remained constant up to 15 days of storage, whereas the anthocyanin content of eggplants stored at 0°C decreased by 73% after 2 days and increased slightly thereafter (Concellón et al. 2007).

Time and Temperature Effects on the Visual Quality of 'Classic' Eggplants

'Classic' eggplants shown in Figures 5.29–5.37 were harvested immature, glossy, with seeds not fully developed, from a commercial operation in Homestead, Florida, during the spring season (i.e., April). Promptly after harvest, fresh eggplants were stored at five different temperatures (0.0 ± 0.3°C, 5.0 ± 0.2°C, 9.4 ± 0.4°C, 14.40 ± 0.4°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Postharvest changes in the external and internal visual quality of 'Classic' eggplants are remarkable when the fruit is stored below or above recommended temperatures. Surface pitting, scalding, bronze-like discoloration, and darkening of the seeds and flesh constitute the major symptoms of visual quality deterioration in eggplants stored at chilling temperatures, whereas shriveling, dryness of the calyx, and fruit softness reduce the quality of the fruit stored at temperatures above 10°C.

'Classic' eggplants stored at 0°C maintain acceptable visual quality for only 2 days (Figure 5.29). After 4 days, pitting of the skin becomes evident, and after 7 days the fruit develops a bronze-like discoloration, which increases as the storage progresses. After 13 days, the appearance of fruit at 0°C is completely deteriorated owing to pitting, discoloration, shriveling, and brownish discoloration of the calyx. Although symptoms of CI are already evident during continuous storage of eggplants at 0°C, upon transfer of the fruit to 20°C for 1 additional day, previously inconspicuous symptoms become evident, or some already obvious symptoms intensify. Although eggplants stored for 2 days at 0°C do not show symptoms of CI during continuous storage, after transfer to 20°C for 1 additional day, the fruit shows severe pitting and scalding. Fruit stored for 12 days at 0°C shows severe discoloration of the entire surface and pitting adjacent to the calyx (Figure 5.30). Internal visual evaluation of the flesh and seeds of those eggplants after transfer to 20°C for 1 additional day shows that after 6 days at 0°C the seeds and the flesh darken; then they become extremely dark brownish after 12 days at 0°C (Figure 5.31).

Symptoms of CI are less severe and develop later in 'Classic' eggplants stored at 5°C compared with fruit stored at 0°C. Incipient pitting develops after 5 days in eggplants stored at 5°C, and after 7 days at 5°C, the fruit develop skin discoloration, which increases as storage progresses. The calyces of the fruits develop a brownish-green color (Figure 5.32). After transfer of the fruit to 20°C for 1 additional day, pitting, scald, and discoloration increase. After 5 days at 5°C, small pits and sunken scald-like lesions develop on the fruit; after 10 days some fruit is severely affected by scalding and pitting. After 13 days at 5°C, discoloration affects most of the fruit surface and calyx (Figure 5.33). After 9 days at 5°C plus 1 additional day at 20°C, the flesh and seeds of the eggplants develop a dark brownish discoloration (Figure 5.34).

'Classic' eggplants stored at 10°C maintain acceptable visual quality for 14 days, yet the calyces become less green with a dry appearance after only 10 days (Figure 5.35). After 16 days at 10°C, shriveling develops on the skin near the calyx, and the fruit appears less glossy, with the calyces less green and more dry and brownish than at harvest. The eggplant flesh appears slightly dry and spongy after 16 days.

Deterioration of 'Classic' eggplants stored at 15°C is rapid. The eggplants maintain acceptable visual quality for just 6 days, yet the calyces are already less green and more dry than at harvest (Figure 5.36). After 7 days, shriveling is evident in the lower part of the fruit and worsens as storage progresses. After 13 days at 15°C, the fruit is extremely shriveled and the calyces appear dry and brown.

Shriveling develops even faster in 'Classic' eggplants stored at 20°C than in fruit stored at 15°C. The eggplants maintain acceptable visual quality for only 4 days at 20°C, but shriveling does not become noticeable until day 5 (Figure 5.37). After 13 days, the fruit is severely shriveled and spongy.

Overall, 'Classic' eggplants maintain better visual quality for the longest period (10–14 days) when they are stored at 10°C compared with storage at lower or higher temperatures. Eggplants stored at 0 or 5°C retain acceptable visual quality for only 2 and 5 days, respectively, but thereafter quality deteriorates rapidly due to CI. The postharvest life and visual quality of eggplants stored at 15 or 20°C is reduced to only 6 and 4 days, respectively, due to shriveling, dryness, and decreased fruit turgidity.

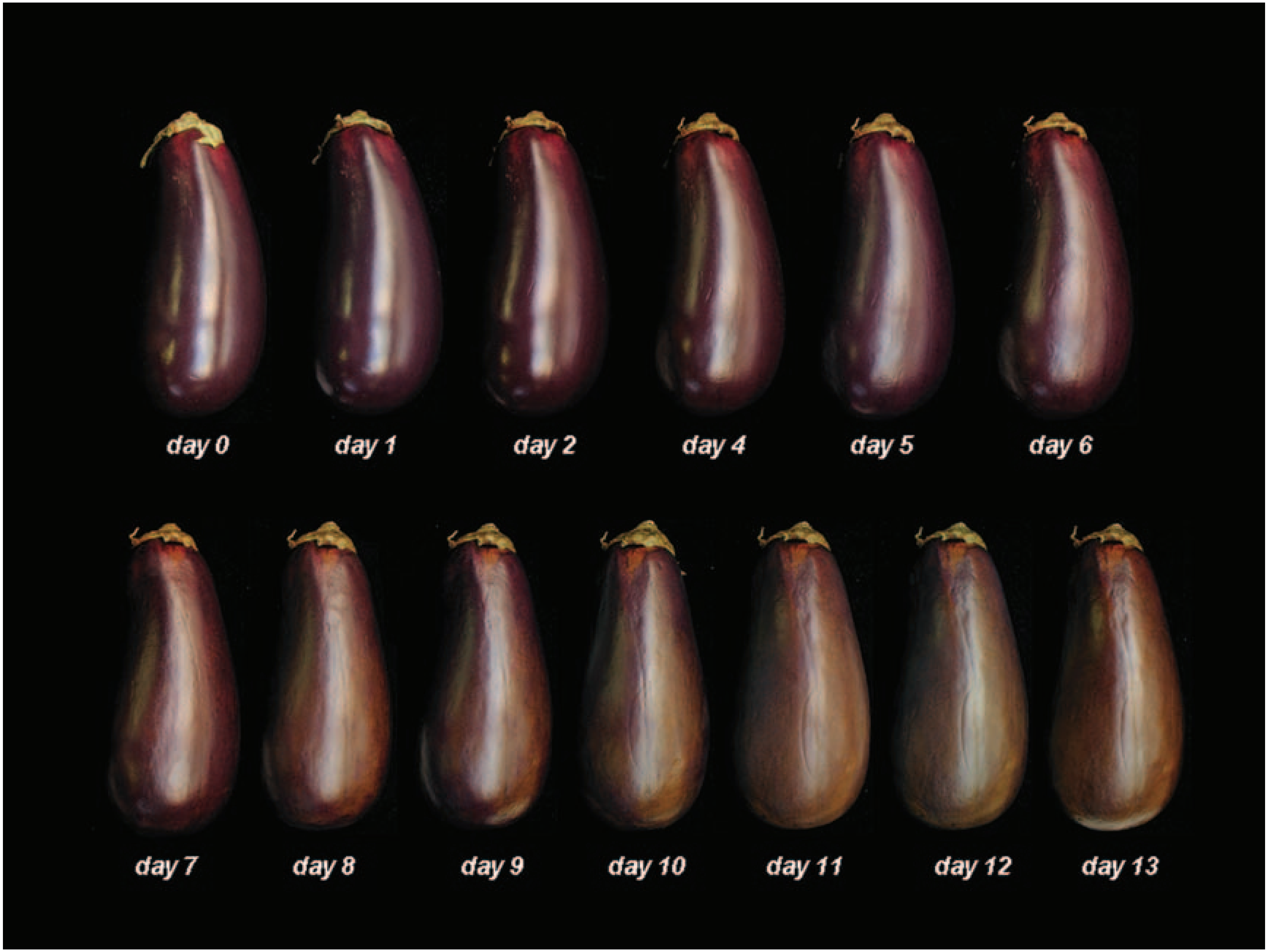
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Figure 5.29. Appearance of 'Classic' eggplants stored for 13 days at 0°C. Eggplants maintain acceptable visual appearance for 2 days at 0°C. Pitting becomes apparent on day 4 and, after 7 days, the fruit develops bronzing of the skin.

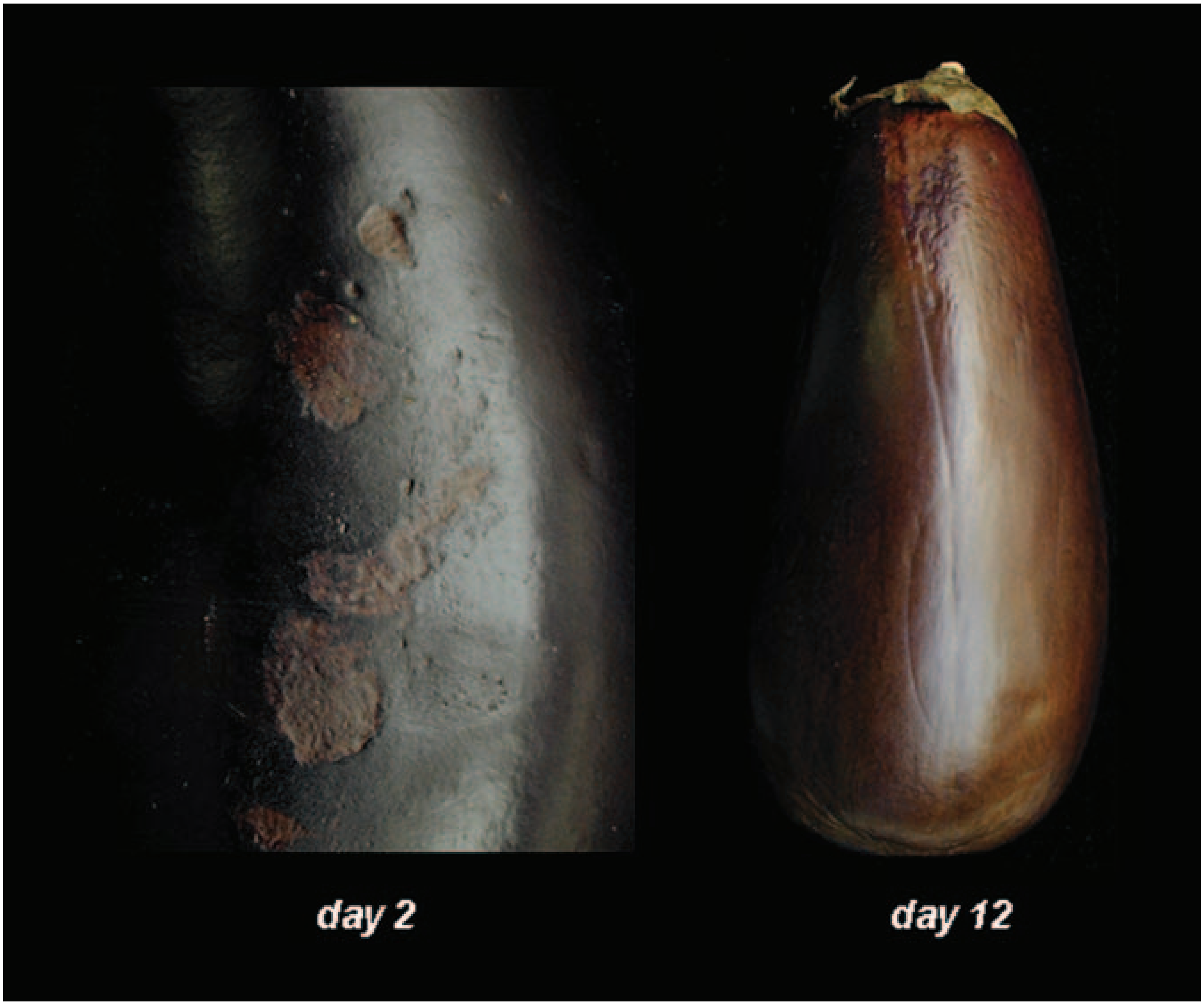

Figure 5.30. Chilling injury (pitting and bronzing of the skin) of 'Classic' eggplants after storage for 2 days (left) or 12 days (right) at 0°C plus transfer to 20°C for 1 additional day.

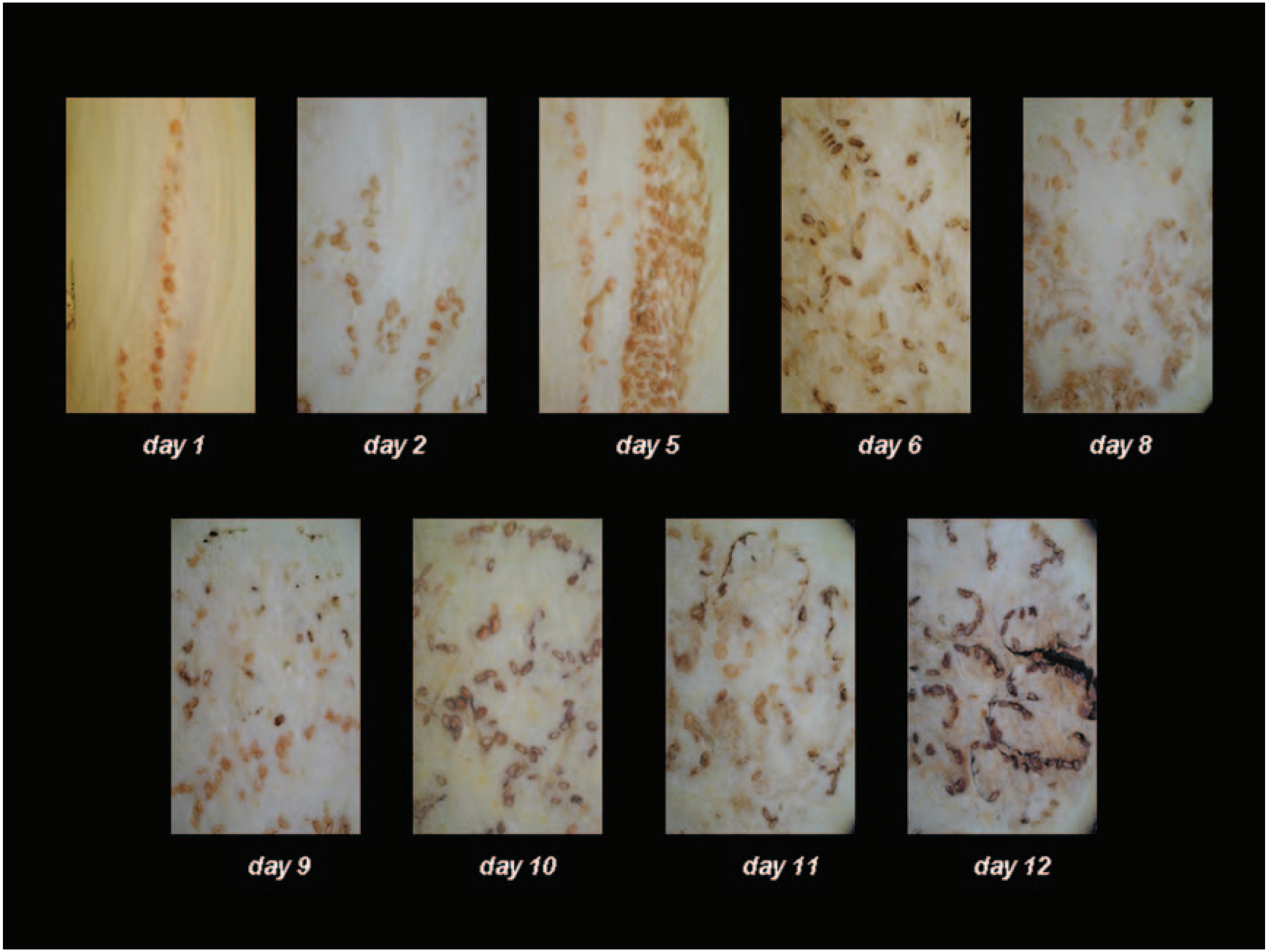
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Figure 5.31. Darkening of the flesh and seeds of ‘Classic’ eggplant stored at 0°C plus transfer to 20°C for 1 additional day.

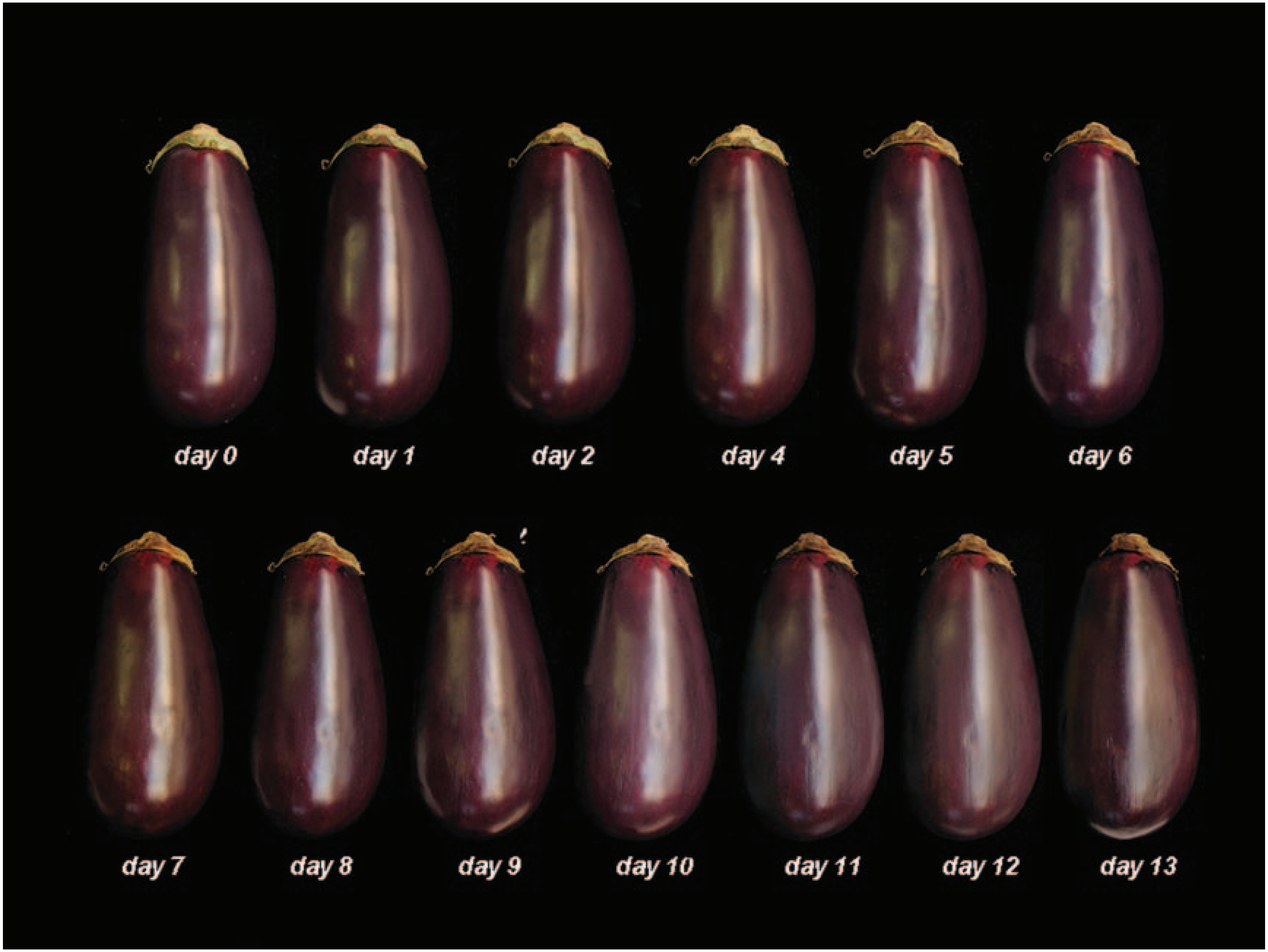
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Figure 5.32. Appearance of ‘Classic’ eggplants stored for 13 days at 5°C. Eggplants maintain acceptable visual appearance for 5 days at 5°C. Pitting becomes apparent on day 6 and, after 7 days, the fruit develops bronzing of the skin.

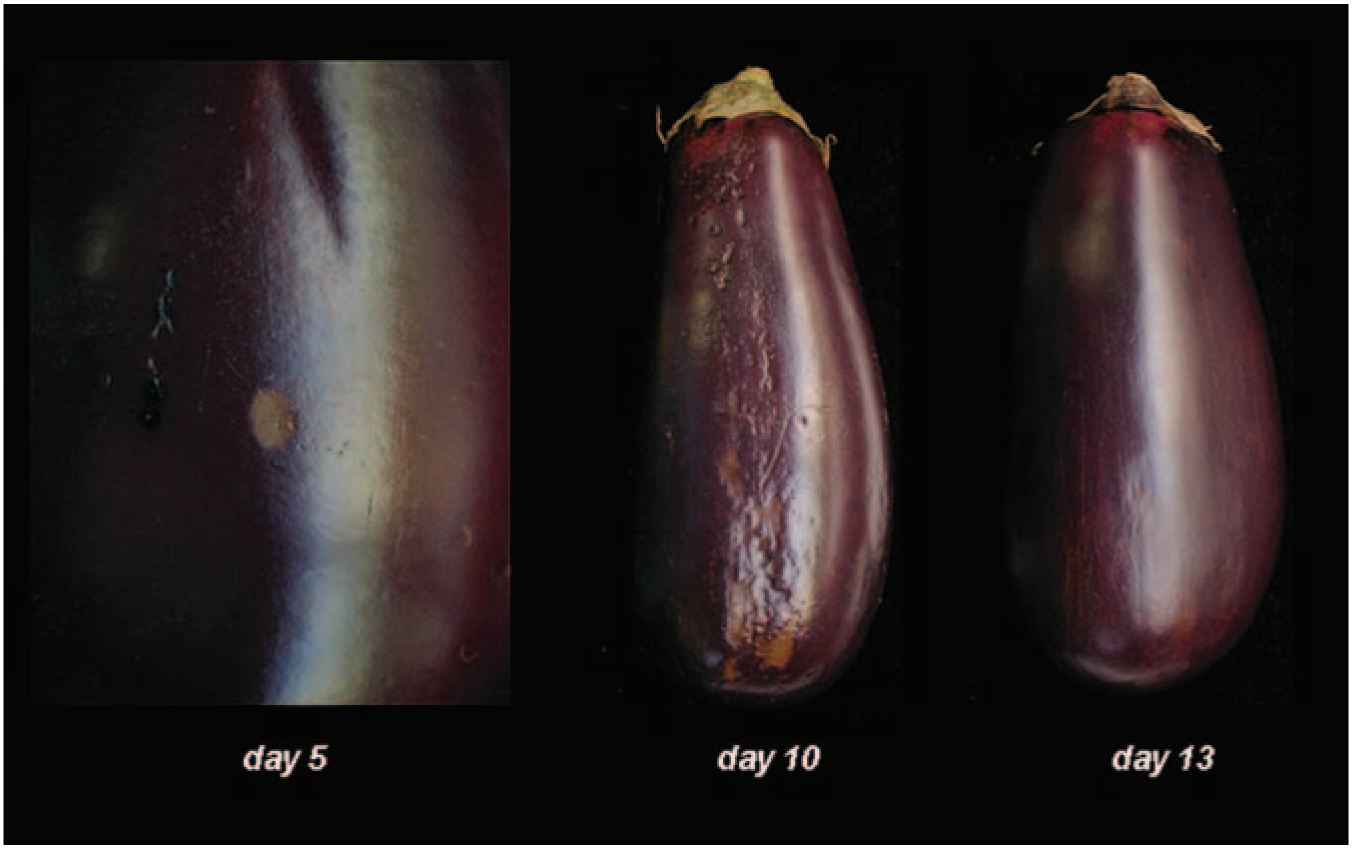

Figure 5.33. Chilling injury (pitting and bronzing of the skin) of ‘Classic’ eggplants after storage for 5 days (left), 10 days (center), or 13 days (right) at 5°C plus transfer to 20°C for 1 additional day.

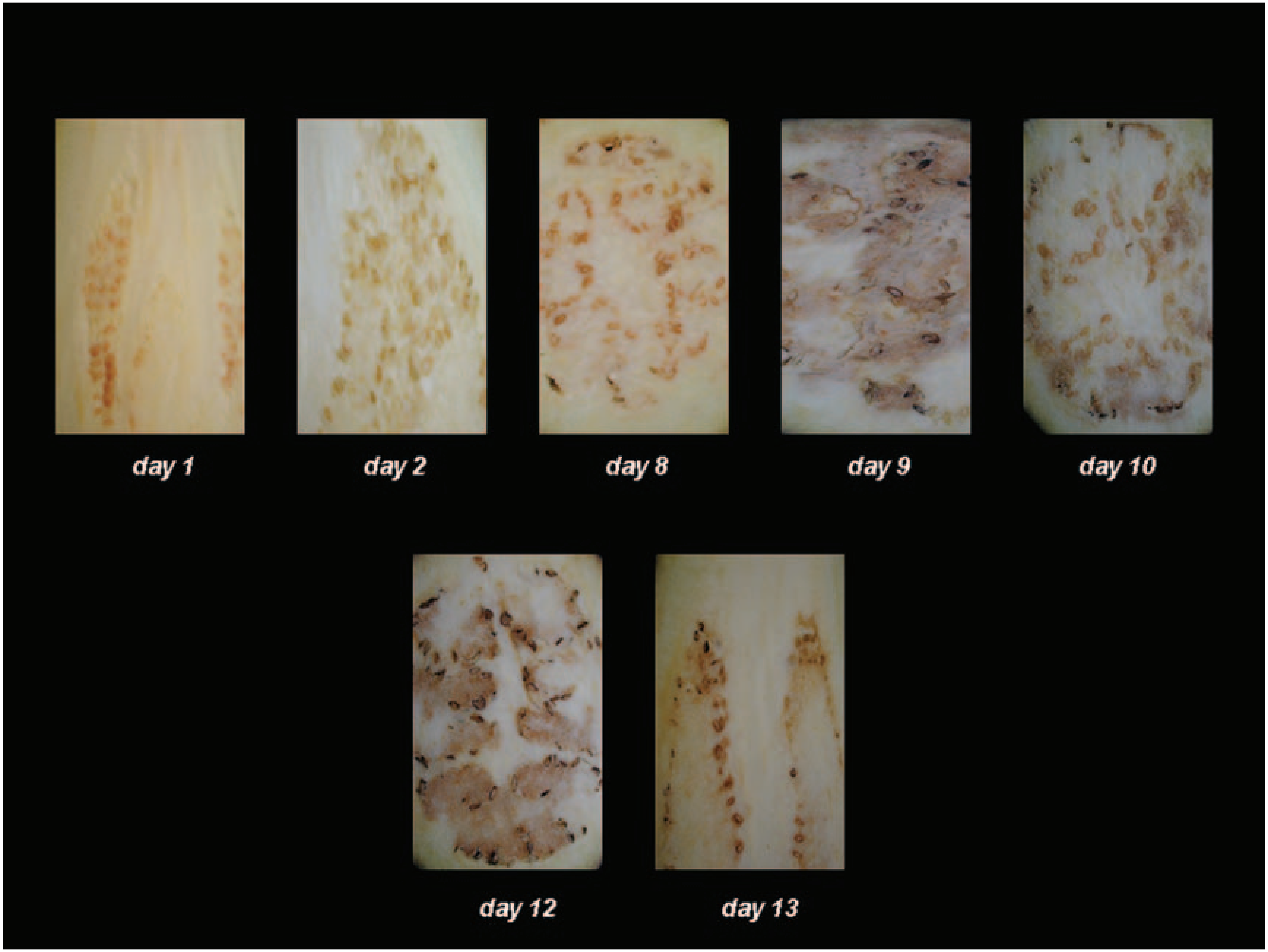
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Figure 5.34. Darkening of the flesh and seeds of ‘Classic’ eggplants stored at 5°C plus transfer to 20°C for 1 additional day.

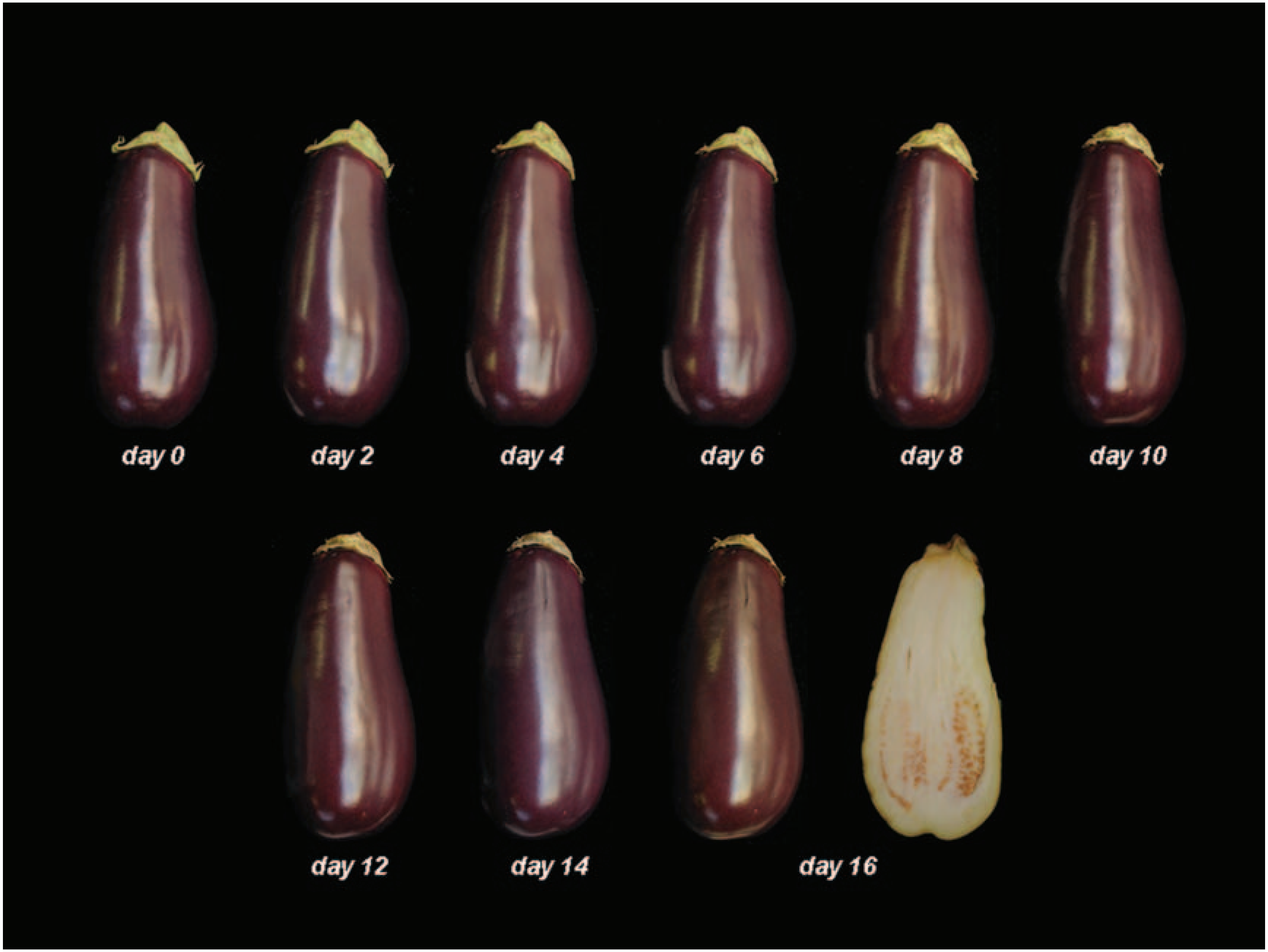
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Figure 5.35. Appearance of 'Classic' eggplants stored for 16 days at 10°C. Eggplants maintain acceptable visual quality for 14 days at 10°C. Slight shriveling of the skin and calyces and flesh dryness develop after 16 days.

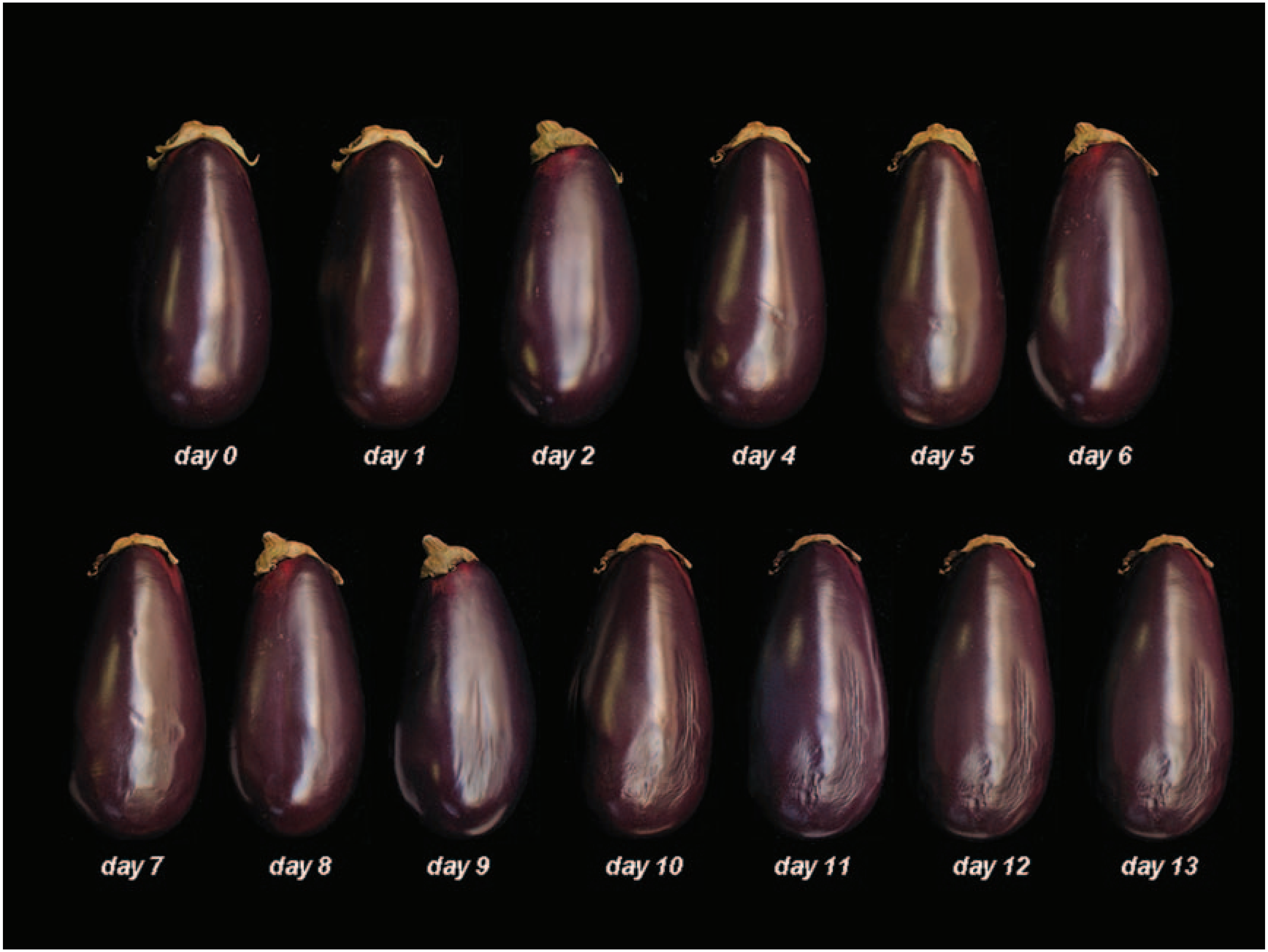
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Figure 5.36. Appearance of 'Classic' eggplants stored for 13 days at 15°C. Shriveling of the skin becomes apparent after 7 days and, after 13 days, the eggplants are extremely shriveled.

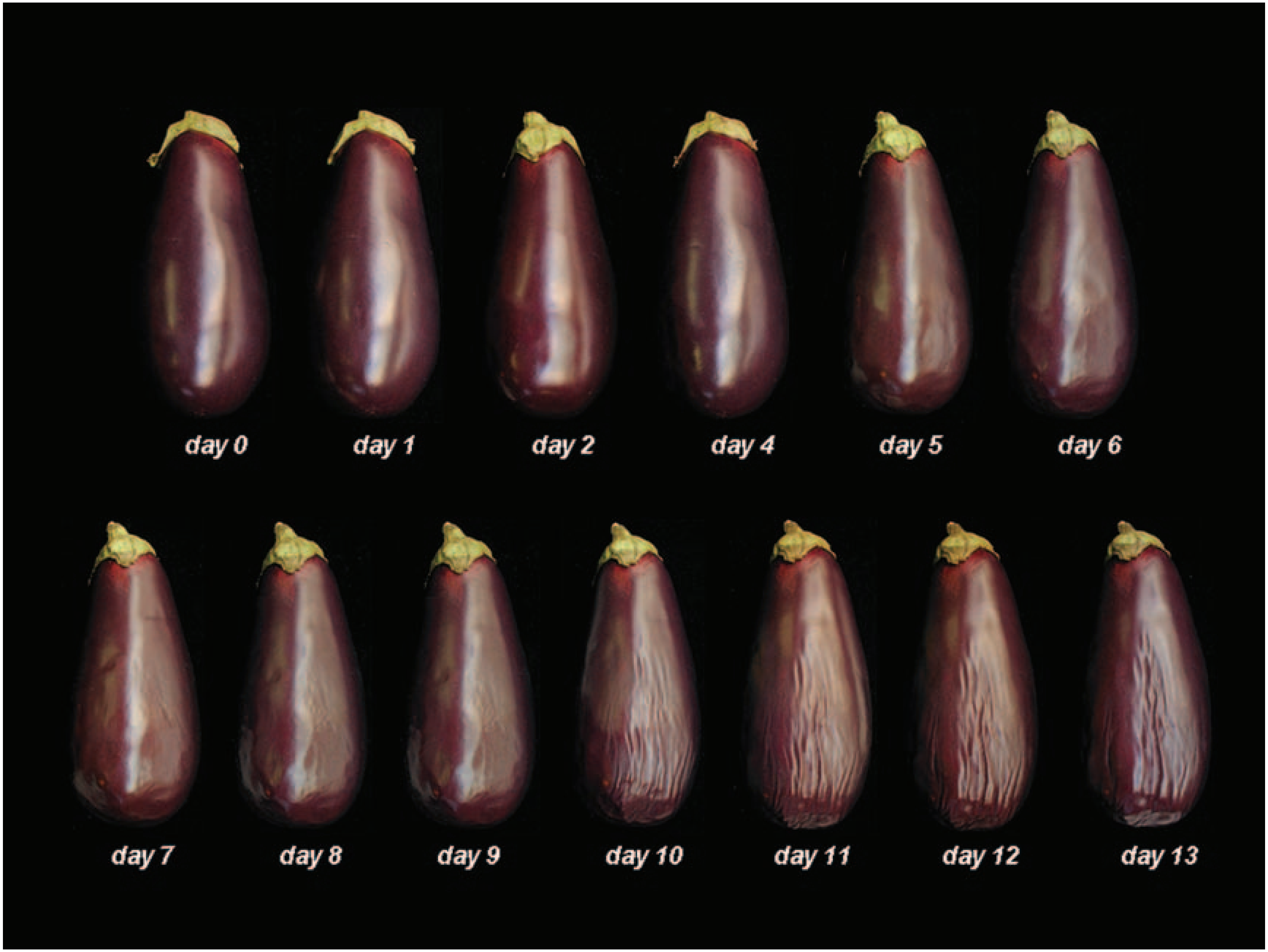
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Figure 5.37. Appearance of 'Classic' eggplants stored for 13 days at 20°C. Shriveling of the skin becomes apparent after 5 days and, after 10 days, the eggplants are extremely shriveled.

SWEETCORN

Scientific Name: *Zea mays* L. var. rugosa Bonaf
Family: Poaceae

Quality Characteristics

Corn is an important horticultural crop native to the Americas. Originating in Mexico, it spread throughout the Americas, to Canada and Argentina, and then to Europe, Africa, and Asia (Benson and Pearce 1987). Sweetcorn is one of the most popular vegetable crops grown in the United States for the fresh market, and in recent years consumption has also greatly increased in Southeast Asia and Europe. Sweetcorn, unlike field corn, contains a mutation of the sugary (*su*) locus on chromosome 4; that is, sweetcorn contains the gene *sugary1* (*su1*) at this locus (Marshall 1987). Traditional varieties of sweetcorn are *su1* mutants that contain about twice the sugar content of field corn, as well as higher water-soluble polysaccharides, which provide the creamy texture for which sweetcorn is known. Newer sweetcorn varieties are *shrunken2* (*sh2*) mutants, also known as "supersweet" sweetcorn. Supersweet varieties have at least double to triple the sugar content of *su1* but almost no water-soluble polysaccharides. Another not so common sweetcorn mutant is the *su1/se1* (*sugary-enhancer*), in which homozygous *se1* modifies homozygous *su1* to also double the sugar content, but without loss of water-soluble polysaccharide content. Although still very perishable, the initial higher sugar content of these supersweet corn varieties combined with inhibited starch synthesis in *sh2* varieties increases the potential postharvest life of sweetcorn (Brecht 2004; Simonne et al. 2006). Although the sugary (*su1*) sweetcorn types have a relatively low sugar content and an expected postharvest life of 5–8 days at 0°C, the supersweet (*sh2*) varieties have a high to very high relative sugar content and an expected postharvest life of 5–19 days (Simonne et al. 2006). In fact, the lowest sugar levels recorded after 2 weeks of storage at 1°C for the *sh2* types were about twice the levels found in *su1* sweetcorn at harvest (Brecht et al. 1990).

Good quality sweetcorn should have uniform size and color typical for the variety (i.e., yellow, white, or bi-color) and should be sweet; the kernels should be plump and milky and not doughy when squeezed, and they should be tender and well developed. The husks should be tight, fresh, and green. Kernel sweetness is the most important quality factor in consumer satisfaction, followed by tenderness and color of the kernels, and sweetness is closely related to sucrose, fructose, glucose, and total sugar concentrations (Brecht 2004; Flora and Wiley 1974; Hale et al. 2004; Kemble 2001; Reyes et al. 1982; Showalter and Miller 1962; Suslow and Cantwell 2006a; Wiley 1985; Wong et al. 1994). The *su1* sweetcorn varieties contain on average 3–5% sugar at harvest, whereas *se1* and *sh2* sweetcorn varieties produce kernels with 7–10% sugar content (Brecht et al. 1990; Geeson et al. 1991; Kemble 2001; Rhodes et al. 1982; Sargent 1999; Showalter and Miller 1962). Conversion of sugar to starch, and the decreased sweetness associated with this change, is as fast in *se1* as in standard *su1* sweetcorn varieties. However, conversion of sugar to starch in *sh2* varieties occurs at a slower rate than in *su1* and *se1* varieties (Kemble 2001; Marshall 1987; Sargent 1999).

Sweetcorn is typically harvested when sugar content reaches maximum levels (around 18–20 days after pollination; Wong et al. 1994). At harvest, sucrose was the predominant sugar in *sh2*, *su1*, and *se1* hybrids, accounting for 76.7–94.1% of the mean total sugar content in *sh2*, 83.4% in *su1*, and 87.7% in *se1* sweetcorn varieties (Wong et al. 1994; Zhu et al. 1992). Glucose followed sucrose in abundance, but fructose and maltose contents were not consistent among the sweetcorn genotypes. Fructose contributed secondly to total sweetness even if glucose was the second in concentration (Zhu et al. 1992). At 20 days after pollination, sucrose concentrations in *sh2* sweetcorn hybrids varied from 33 to 371 mg/g dry weight, whereas total sugar content ranged from 133 to 455 mg/g dry weight. Sweetcorn ears harvested 20 days after pollination had the highest kernel sucrose content and total sugar concentrations, which dropped by 36% at 29 days after pollination (Wong et al. 1994). Differences in the individual sugars between sweetcorn varieties was found to occur mainly in sucrose, which is the dominant sugar, suggesting that sweetness differences between sweetcorn cultivars is primarily the result of the difference in sucrose content (Hale et al. 2005; Reyes et al. 1982). Therefore, sucrose concentrations can be used to distinguish the overall sweetness of sweetcorn varieties, especially *su1* and *sh2* genotypes. *Sh2* had higher levels of sucrose at all maturity stages compared with *su1* or *se1*. The decrease in sucrose content in *su1* and *se1* sweetcorn varieties at maturity was attributed to reductions in sucrose, fructose, and glucose contents and starch formation in overmature sweetcorn (Hale et al. 2005). Changes in starch content parallel changes in sugar content—as starch content increases with kernel maturity, sugar content decreases. Starch content of sweetcorn increased from 8% in completely immature, white, small, and incompletely filled-out sweetcorn cobs to 10% in slightly immature, light yellow cobs and 15% in mature to overmature kernels (Maywald et al. 1955).

Textural eating quality of sweetcorn consists of several factors, including pericarp tenderness, level of water-soluble polysaccharides, and moisture content. The accumulation of water-soluble polysaccharide gives sweetcorn its creamy texture, particularly in the *su1* varieties, which have water-soluble polysaccharide content 8–10 times higher than field corn (Brecht 2004; Marshall 1987). Although *sh2* sweetcorn varieties may be sweeter than *se1* or *sh2* varieties, their pericarp may be tougher than the other sweetcorn varieties. Greatest tenderness scores were attributed to *se1* sweetcorn varieties followed by *sh2*, with *su1* varieties receiving the lowest tenderness scores (Hale et al. 2004).

With increasing maturity, toughening of the kernels increases and moisture content decreases. At 20 days after pollination, kernel moisture content in *sh2* hybrids ranged from 73.1 to 76.8%. A drop of 5.2% in kernel moisture content among the *sh2* hybrids was observed from 20 to 29 days after pollination, or 0.6% per day (Wong et al. 1994). Kernel moisture decreased from 84% in completely immature, white, small, and incompletely filled-out sweetcorn cobs to 71% in slightly immature, light yellow cobs and 68–65% in mature to overmature cobs, respectively (Maywald et al. 1955).

On average, mature white and yellow sweetcorn contains 75–77% water, 3.2% protein, 19% carbohydrates, 3.2–10% total sugars, 2.7–4.3% fiber, and 6.8 mg ascorbic acid per 100 g fresh weight (Aung et al. 1992; Brecht et al. 1990; Kemble 2001; Marlett and Vollendorf 1993; Rhodes et al. 1982; Sargent 1999; Showalter and Miller 1962; USDA 2006). Yellow sweetcorn contains between 8.4 and 52 μg β-carotene per 100 g fresh weight (Lee et al. 1981; USDA 2006). The carotenoid content of sweetcorn genotypes selected on the basis of color showed that dark yellow kernels have the greatest total carotenoid levels followed by light yellow, orange, and pale yellow. Genotypes with dark yellow kernels were also generally high in β-carotene content, whereas lutein and α-tocopherol were significantly higher in the *sh2* varieties compared to the *su1* and *se1* varieties (Kurilich and Juvik 1999).

Optimum Postharvest Handling Conditions

Sweetcorn is highly perishable, and overall quality deteriorates rapidly after harvest. Therefore, rapid removal of field heat is critical to retard loss of moisture, kernel denting, and loss of sweetness. Maximum quality is retained by pre-cooling sweetcorn to 0°C within 1 hour after harvest, and subsequently holding it at 0°C and 95–98% relative humidity (Brecht 2004; Suslow and Cantwell 2006a). Sweetcorn is commonly hydro-cooled or vacuum-cooled in wooden crates. Vacuum-cooling is the fastest method for pre-cooling of sweetcorn; however, the ears should be properly wetted prior to vacuum pre-cooling to avoid excessive loss of water (Sargent 1999; Talbot et al. 1991). Insufficient wetting of the sweetcorn ears prior to vacuum-cooling may result in a 1% moisture loss for each 10°C drop in sweetcorn temperature, and denting of the kernels may occur (Sargent 1999). However, hydro-cooled sweetcorn tends to lose less water than forced-air or vacuum-cooled sweetcorn, resulting in kernels with higher moisture content (Talbot et al. 1989; Vigneault et al. 2007; Wilhelm et al. 1992).

Temperature Effects on Quality

Kernel moisture and sugar content are closely related to sweetness, tenderness, and succulence, and constitute the most important quality attributes of sweetcorn. In general, kernel moisture content, succulence, and flavor decrease, whereas pericarp thickness increases with increasing storage temperature and time (Brecht 2004; Brecht et al. 1990; Kramer et al. 1949). All sweetcorn varieties lose sweetness and aroma during storage, but the taste of *su1* and *se1* varieties becomes starchy, whereas *sh2* will taste watery and bland (Brecht 2004). Loss of tenderness, sweetness, and flavor volatiles, which largely determine sweetcorn quality, are rapid after harvest and are greatly affected by the storage temperature. The loss of sugar is about four times greater at 10°C than at 0°C, and at 30°C, 50–60% of the sugar in *su1* sweetcorn can be converted to starch in a single day, whereas only 6% is converted at 0°C. Although *sh2* varieties lose sugar as fast as *su1* varieties (due to respiration), their initial sugar content keeps the corn sweeter for longer periods (Amir et al. 1971; Brecht et al. 1990; Olsen et al. 1990). For *sh2* varieties, water loss and pericarp toughening occur faster than loss of sweetness and thus limit sweetcorn postharvest life (Brecht et al. 1990).

In general, *su1* sweetcorn maintains acceptable appearance during 5–8 days at 0°C, but postharvest life is reduced to 3–5 days at 5°C, and to about 2 days at 10°C (Sargent 1999). Supersweet (*sh2*) sweetcorn stored at 1, 4, 7, or 13°C was much sweeter than either *se1* or *su1* sweetcorn after 7 days; however, the difference in sweetness was most pronounced in sweetcorn stored at 13°C. Sweetness ratings of *sh2* sweetcorn after 7 days of storage were not markedly reduced at 7 or 13°C. However, both *se1* and *su1* sweetcorn types were rated not sweet after 7 days at 13°C (Olsen and Jordon 1989). Total sugar content of sweetcorn stored at 0 or 10°C decreased continuously during storage, whereas starch content initially increased and then decreased (Evensen and Boyer 1986; Türk et al. 2001). Yet total sugar and sucrose contents were in general lower and starch content higher in sweetcorn stored at 10°C compared with 0°C (Evensen and Boyer 1986). Although total sugar content tended to decrease with increasing storage temperature, after 10 days of storage at either 1, 4, 7, or 18°C, the total sugar content of 'Sucro' *sh2* sweetcorn was higher (7.1, 6.6, 5.4, and 2.0%, respectively) than the sugar content of 'Aussie

Gold 12' *su1* sweetcorn (1.4, 2.4, 1.0, and 1.1%, respectively) and 'Rosella 425' *su1* sweetcorn (1.1, 2.2, 1.2, and 1.0%, respectively). This indicates that *sh2* sweetcorn may be expected to be almost as sweet as the fresh *su1* cultivars after 10 days after harvest, even when held at 18°C. Fructose, glucose, and sucrose contents tended to decrease with increasing storage time and temperature, regardless of the sweetcorn cultivar, whereas starch content increased (Olsen et al. 1990; Rumpf et al. 1972). Starch content of yellow and white sweetcorn cultivars was significantly higher in sweetcorn held at 20°C (157.0 and 177.4 mg/g dry weight, respectively) compared to sweetcorn stored at 10°C (148.1 and 152.5 mg/g dry weight, respectively) (Deák et al. 1987). However, the decrease in sucrose content during storage of sweetcorn at 0, 5, or 10°C was significantly higher compared with the decrease in glucose or fructose (Rumpf et al. 1972). Nevertheless, after 10 days of storage at 18°C, fructose and sucrose contents were significantly higher and starch content significantly lower in *sh2* sweetcorn compared to *su1* or *su* (Olsen et al. 1990).

Soluble solids content is considered an unreliable measure to estimate total sugars or sucrose content of sweetcorn for determining when to harvest because it is negatively correlated with the total sugar and sucrose contents. That is, as soluble solids content increases, the total sugar and sucrose contents can decrease. The increase in soluble solids content is attributed to the continued increase in water-soluble polysaccharides with increasing sweetcorn maturity—after the point at which kernel sugar content no longer increases on the plant (Hale et al. 2005; Zhu et al. 1992). Nonetheless, after harvest, the soluble solids content of three *se1* sweetcorn varieties decreased rapidly with increasing storage temperature and time (Vigneault et al. 2007). Loss of total soluble solids after 21 days of storage at 1°C was higher for 'Promise' and 'Fleet' (17% and 16%, respectively), followed by 'Sensor,' with 8.7% loss. Risse and McDonald (1990) reported that after 14 days at 10°C, bicolor 'Candy Store' (*su*, *se*) sweetcorn had lost approximately 47% of its initial soluble solids content (16.3%), whereas the same sweetcorn stored at 1°C lost approximately 22%. After 21 days at 1°C, the sweetcorn had lost approximately 25% of its initial soluble solids content (from 16 to 12%).

Loss of green color in the leaves of the husk and kernel denting are indicators of loss of moisture and overall quality of sweetcorn. A loss of moisture of only 2% from sweetcorn may result in objectionable kernel denting (Kemble 2001; Sargent 1999), whereas a 7% water loss is considered to be the maximum that is acceptable before sweetcorn becomes unacceptable for sale (Robinson et al. 1975). Trimming the shanks and flag leaves before marketing helps to retard kernel denting caused by loss of moisture, and reduces ear weight loss (Showalter 1967). Kernel moisture content decreased from an initial value of 70.7% at harvest to 67.4%, 65.6%, and 62.3% after 7 days of storage at 1.5, 21, and 31°C, respectively (Kramer et al. 1949). Consequently, kernel succulence and flavor decreased, whereas pericarp content increased with increasing storage time and temperature.

Plastic films are often used at the retail level to wrap sweetcorn, particularly de-husked cobs, in order to reduce moisture loss and kernel denting, and to maintain a fresh appearance while providing the consumer with a view of the internal appearance of the sweetcorn. Film packaging of husked sweetcorn ears provides protection against kernel denting and moisture loss, similar to that of ears in the husk with shanks and flags removed. Completely husked ears packed in plastic film showed trace of denting and 1.0% weight loss, whereas nontrimmed sweetcorn showed severe kernel denting and 22% weight loss after 6 days of storage at 10°C (Showalter 1967). Likewise, trimmed sweetcorn wrapped in stretch-wrapped or shrink-wrapped films had a fresher appearance, was greener, showed less drying and less kernel denting, and had higher total soluble solids and sugar contents than nonwrapped corn (Aharoni et al. 1996; Deák et al. 1987; Manleitner et al. 2003; Risse and McDonald 1990).

The high relative humidity inside sweetcorn packages can also accelerate microbial growth (Aharoni et al. 1996; Deák et al. 1987; Risse and McDonald 1990; Rodov et al. 2000). For example, sweetcorn wrapped in polyvinylchloride film had only 1.1–1.4% weight loss after 12 days at 1°C plus 2 additional days at 20°C, but decay levels were between 45 and 51% at the cut ends (Aharoni et al. 1996). Similarly, Deák et al. (1987) reported that although losses of kernel moisture from shrink-wrapped, de-husked white sweetcorn or unhusked yellow sweetcorn were greatly reduced during storage at 10 or 20°C compared with that of unwrapped sweetcorn, the shelf life of the wrapped sweetcorn was limited by the appearance of microbial growth within 5 days of storage at 20°C for the white cobs, and the yellow ears showed similar deterioration after 10 days at 20°C. The kernels became discolored, slimy, and moldy in appearance, whereas the husks turned brown and mold developed.

Time and Temperature Effects on the Visual Quality of 'Prime Time' Sweetcorn

'Prime Time' yellow supersweet (shrunken-2) corn shown in Figures 5.38 through 5.43 was harvested at commercial maturity (pollination silks dried and kernels still immature; husk leaves tight with a good green appearance; ear firm and turgid; kernels plump and not doughy when squeezed) from a commercial operation in Homestead, Florida, during the spring season (i.e., April). Before storage, husks and silks were completely removed and sweetcorn ears were stored at five different temperatures (0.0 ± 0.3°C, 5.0 ± 0.2°C, 9.4 ± 0.4°C, 14.40 ± 0.4°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Quality evaluation of 'Prime Time' yellow *sh2* sweetcorn ears shows that kernel denting, general dry appearance of the cob, and development of decay constitute the major visual quality changes during storage. Sweetcorn stored at 0°C maintains acceptable visual quality for 12 days, with only slight dryness noticeable on the tips of the cobs (Figure 5.38). At this temperature, the sweetcorn kernels maintain a turgid and compact appearance with no signs of denting. However, the kernels are slightly less sweet and succulent after 12 days of storage than at harvest.

'Prime Time' sweetcorn stored at 5°C maintains acceptable visual quality for 11 days, with no signs of kernel denting. The extremities of the cob become drier after 12 days, and some kernels at the butt-end of the cob show denting (Figure 5.39). Sweetness and succulence of the kernels are somewhat lower after 11 days than at harvest.

After 7 days at 10°C, 'Prime Time' sweetcorn shows some slight denting of the kernels and dryness of the extremities of the cob (Figure 5.40). As storage progresses, more kernels develop a dented and less turgid appearance, and after 12 days the entire cob appears dry. At this temperature, loss of sweetness is very fast and, after 7 days, the kernels are unquestionably less sweet and succulent, and the pericarp is tougher than at harvest.

Deterioration of sweetcorn stored at 15°C is rapid. After 3 days, kernel denting becomes evident on some kernels, and the tips of the cobs appear dry and shriveled. After 6 days, decay develops on the tips of the cobs (Figure 5.41). After 12 days, the entire cob appears dry with severe kernel denting, and decay affects more kernels at the tips of cobs. After 3 days, when the first kernel denting develops, the kernels are tough, less succulent, and have a bland taste. Figure 5.43 shows the appearance of the cobs and a close view of the kernels after 4 days at 15°C. Kernel denting is evident and affects the entire cob, which appears dry with the kernels no longer tightly appressed to each other.

Kernel denting and dryness develops extremely quickly in 'Prime Time' sweetcorn stored at 20°C. After 2 days, slight kernel denting develops on some of the kernels, and after 3 days the entire cob appears dry and the kernels are severely dented, dry, and separated from each other (Figure 5.42). The taste of the kernels is bland after 2 days at 20°C compared with the taste at harvest. Figure 5.43 shows the appearance of the cob and a close view of the kernels after 3 days at 20°C, with significant kernel denting and dryness apparent that affects the entire cob. Some of the dented kernels also develop brownish discoloration. After 6 days, decay becomes evident at the stem-ends of the cobs where some remains of husks are still attached, and the decay develops quickly as storage progresses. After 8 days at 20°C, the kernels at the stem-ends of the cobs and at the tips are also affected by decay. After 12 days, the sweetcorn appears completely dry and shriveled and scattered with spots of mold.

Overall, 'Prime Time' *sh2* sweetcorn stored without its husk maintains a better visual appearance for a longer period when stored at 0 or 5°C (12 or 11 days, respectively) compared with storage at higher temperatures. However, after 7, 3, and 2 days at 10, 15, and 20°C, respectively, the visual quality of the sweetcorn is severely deteriorated.

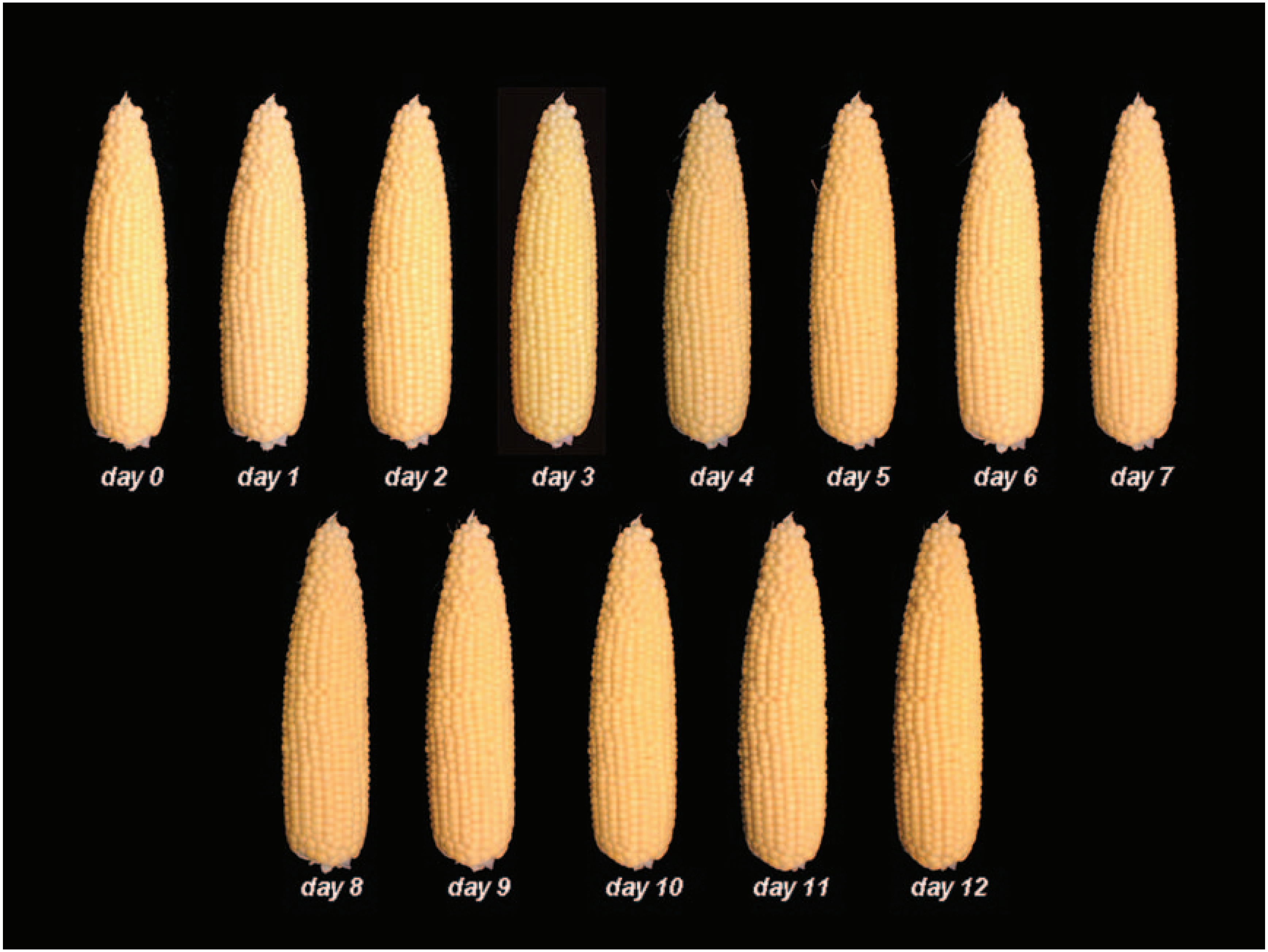
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Figure 5.38. Appearance of 'Primetime' sweetcorn cobs stored for 12 days at 0°C. Sweetcorn maintains acceptable visual quality for 12 days at 0°C, yet slight dryness develops on the tips of the cobs.

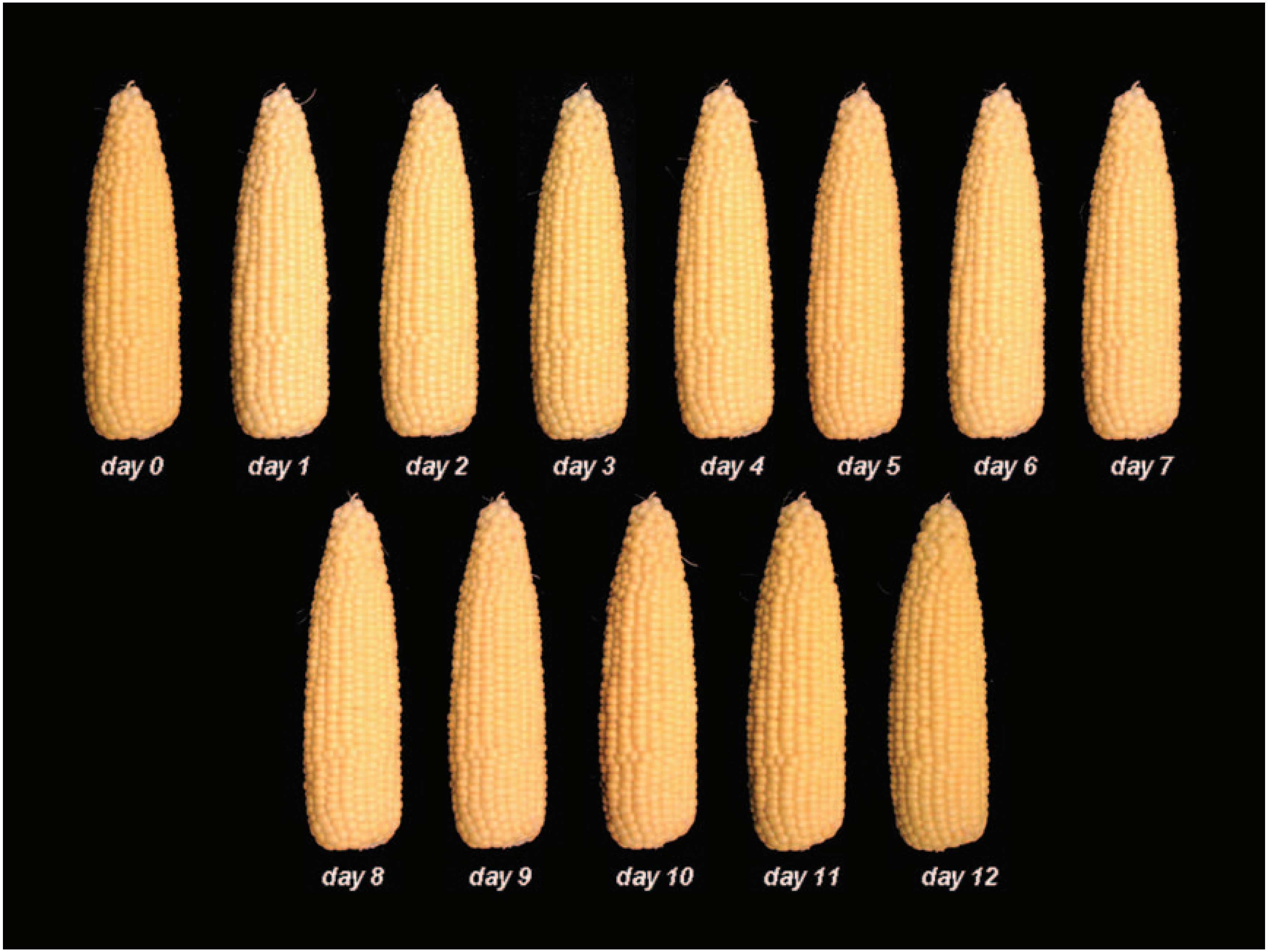
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Figure 5.39. Appearance of ‘Primetime’ sweetcorn cobs stored for 12 days at 5°C. Sweetcorn maintains acceptable visual quality for 11 days at 5°C, yet slight dryness develops on the tips and stem-ends of the cobs.

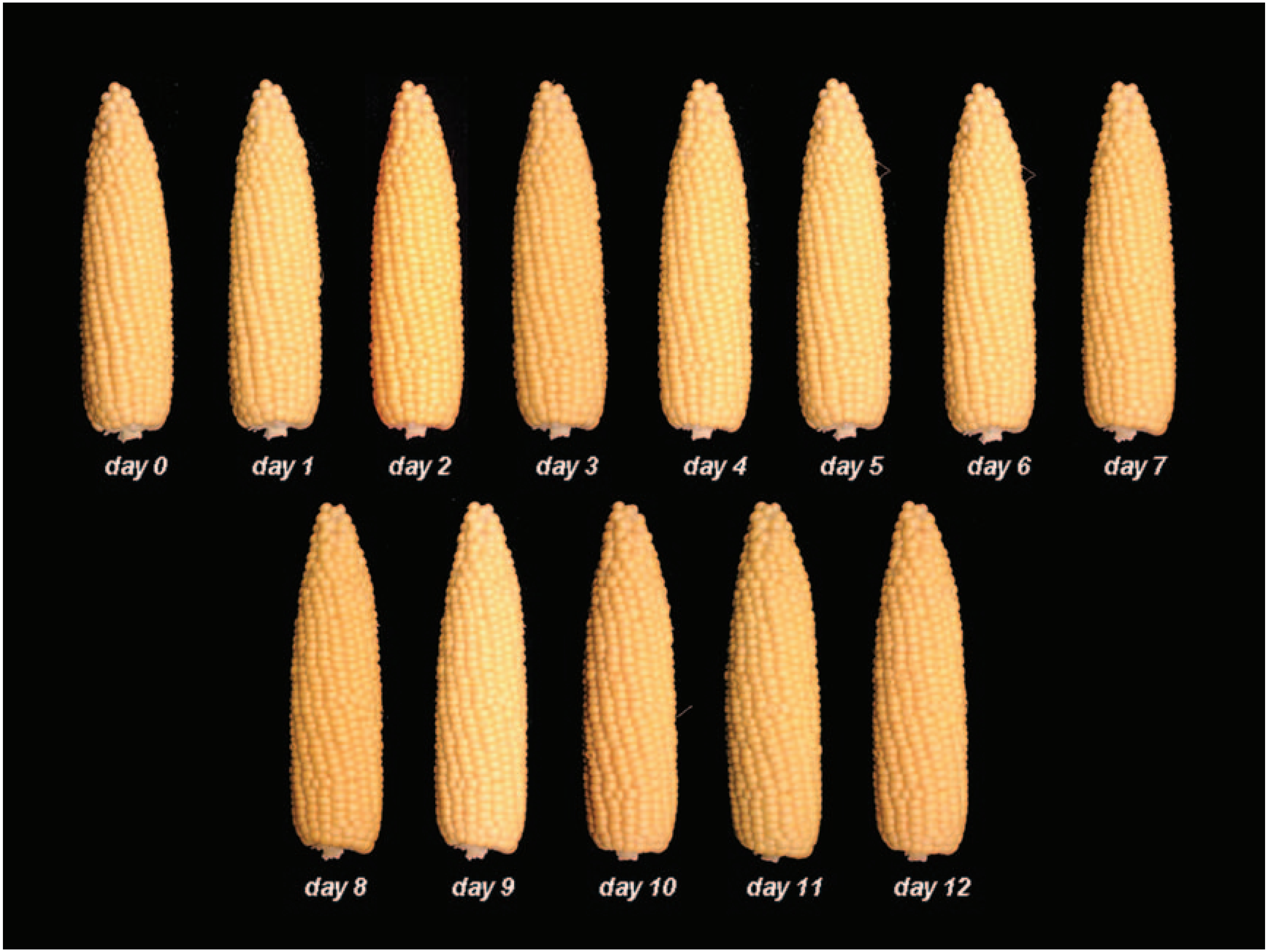
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Figure 5.40. Appearance of 'Primetime' sweetcorn cobs stored for 12 days at 10°C. After 7 days, denting becomes apparent on some kernels.

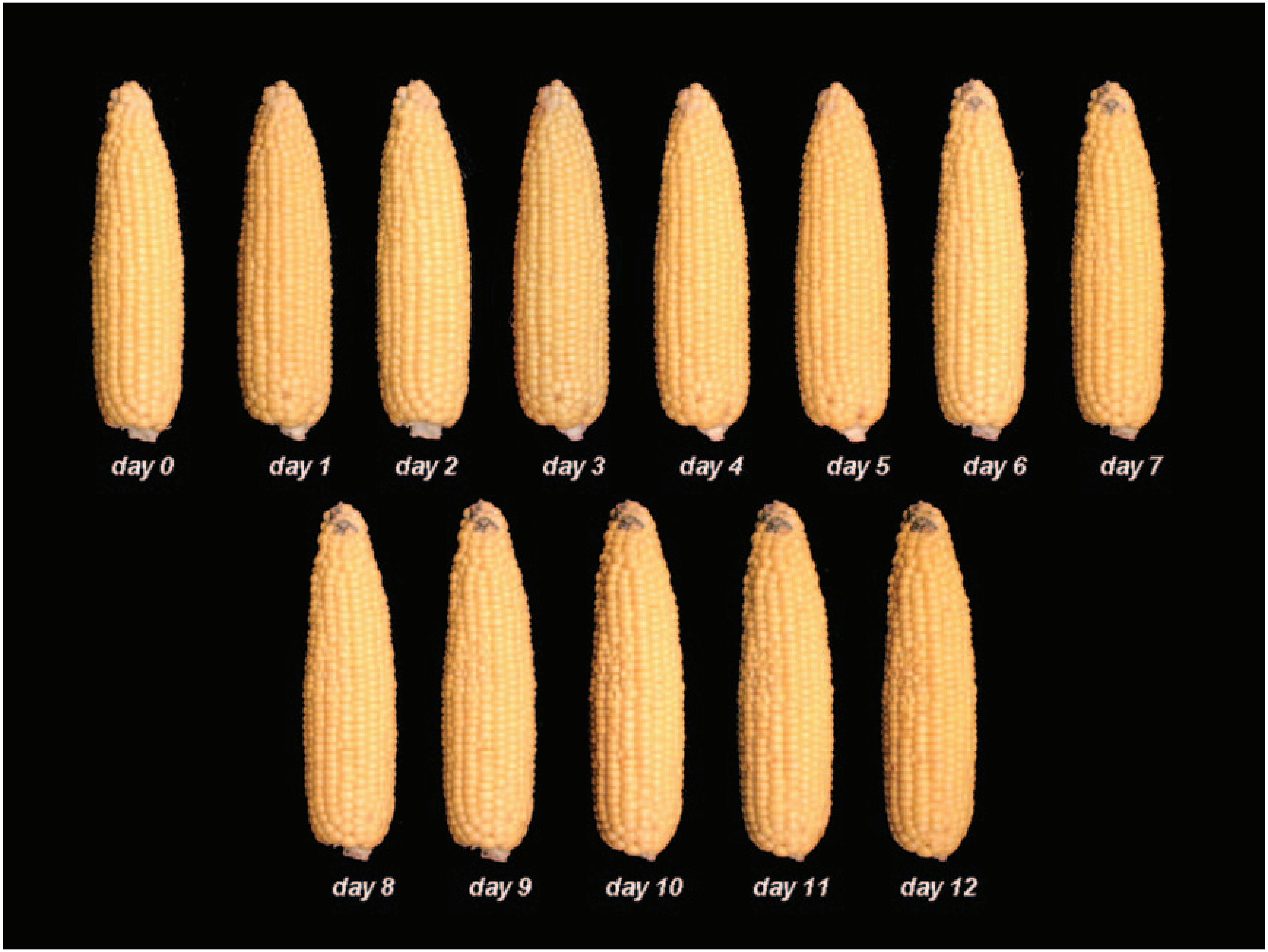
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Figure 5.41. Appearance of 'Primetime' sweetcorn cobs stored for 12 days at 15°C. After 3 days, denting becomes apparent on some kernels and, after 6 days, decay develops on the tips of the cobs.

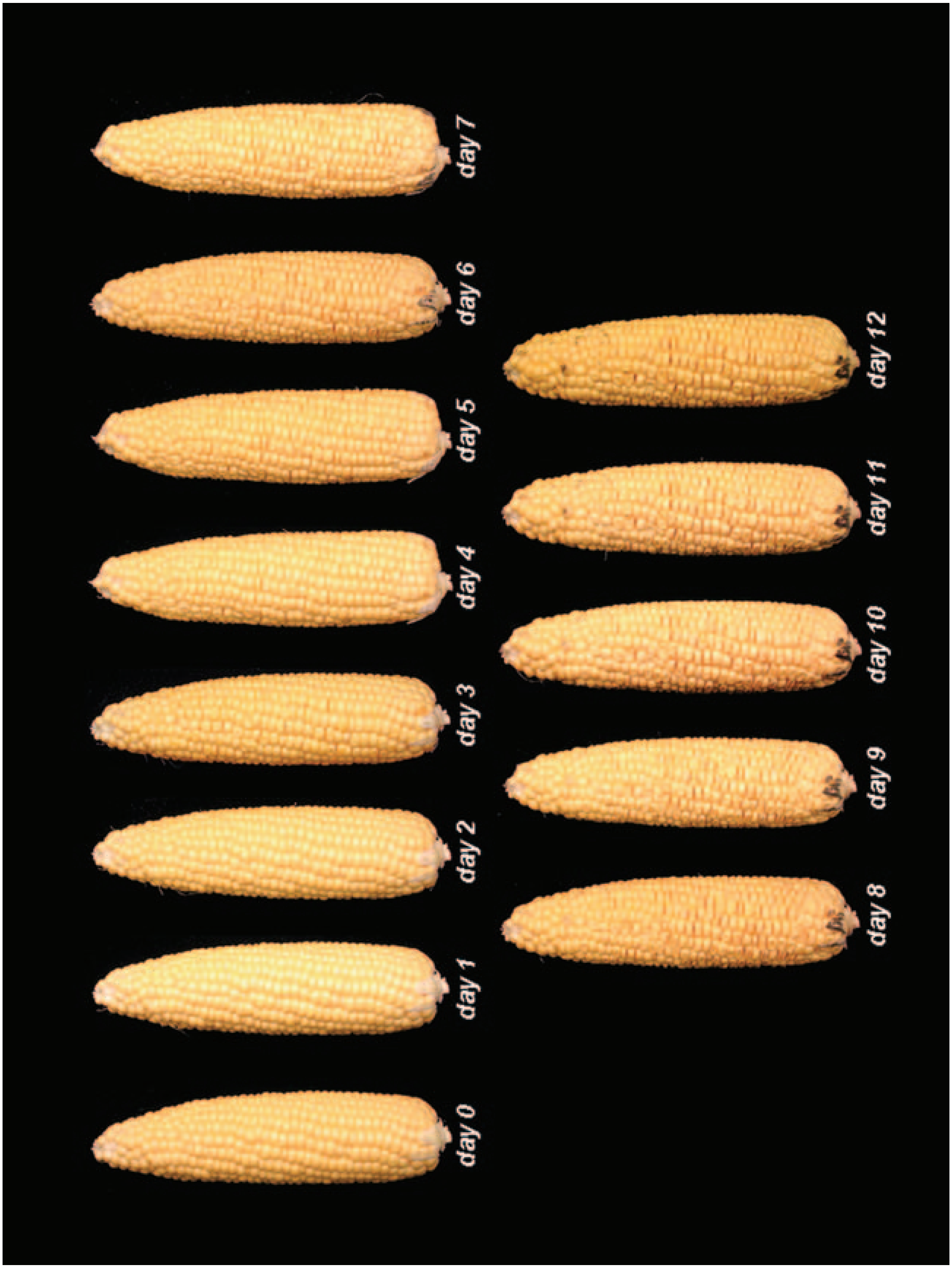
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Figure 5.42. Appearance of ‘Primetime’ sweetcorn cobs stored for 12 days at 20°C. After 3 days, the sweetcorn cobs appear dry and the kernels shriveled.

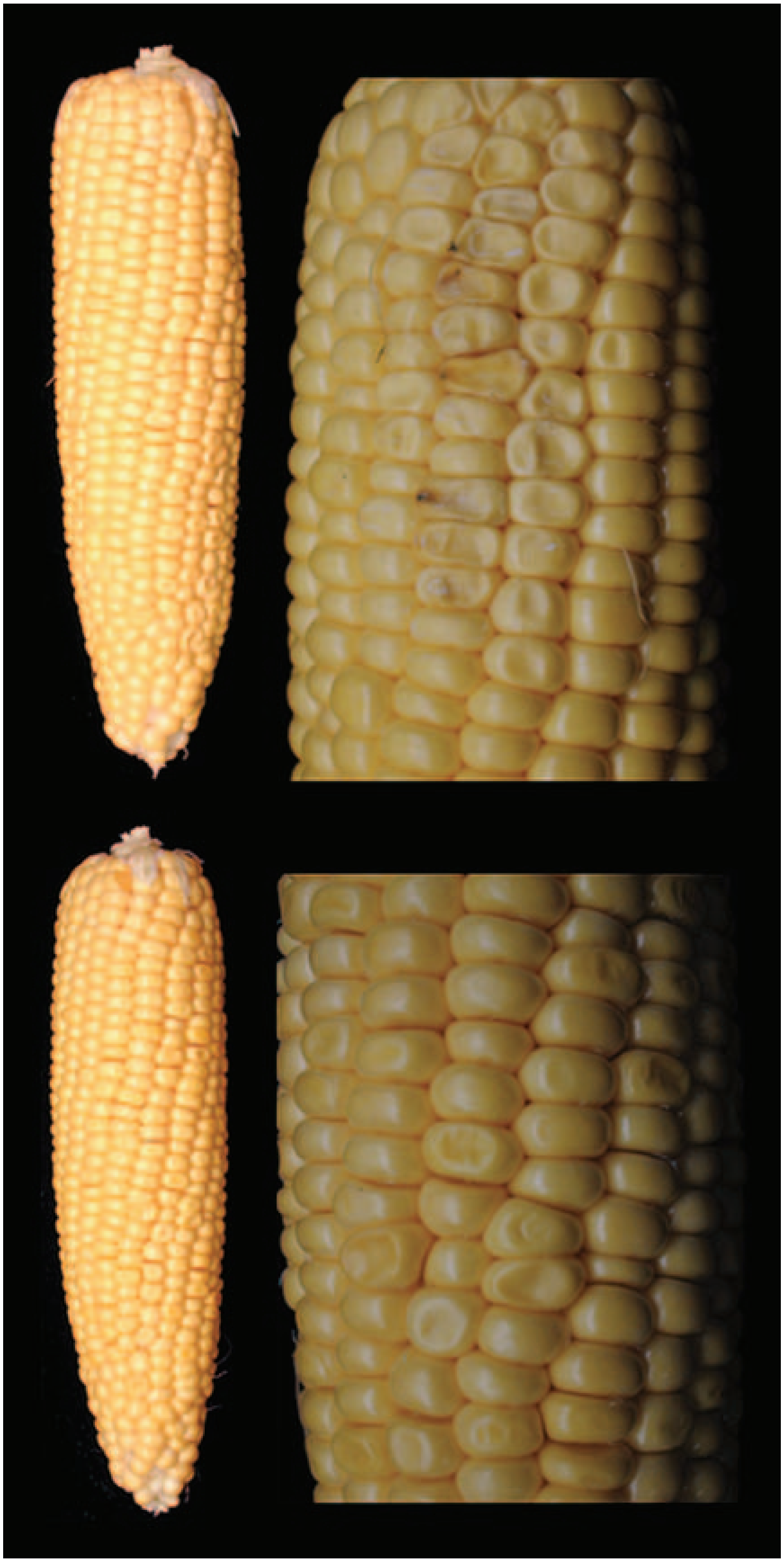

Figure 5.43. Kernel denting of 'Primetime' sweetcorn cobs after storage for 4 days at 15°C (left) and after 3 days at 20°C (right).

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CHAPTER 6

LEGUMES AND BRASSICAS

Faba Bean
Snap Bean
Cabbage
Cauliflower
Broccoli
Brussels Sprouts
Bibliography

Color Atlas of Postharvest Quality of Fruits and Vegetables Maria Cecilia do Nascimento Nunes
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FABA BEAN

Scientific Name: *Vicia faba* L.
Family: Fabaceae

Quality Characteristics

Faba bean is also known by many other names, such as fava bean, broad bean, horse bean, Windsor bean, English bean, tick bean, field bean, and pigeon bean. Most of these names, however, refer to a particular group rather than to the whole species. Therefore, in order to facilitate and standardize the terminology, the name faba has been adopted to designate the entire species (Hawtin and Hebblethwaite 1983). Faba bean is a popular vegetable in the Middle East, Asia, Europe, Australia, and in some regions of North and South America, but it is uncommon in the United States. The faba bean fruit is a broad leathery pod, with a green and thick pod coat when immature that turns to a blackish-brown color when mature. It has a dense velvety internal surface that protects the seeds, which are light green, large, and flat. The pod length ranges from 5 to 25 cm long and from 2 to 3 cm thick. Each pod contains on average three to eight round to oval light green seeds that may vary in size, depending on the cultivar and maturity. The seeds are formed by two cotyledons that are enveloped by a hull. The thickness and hardness of the hull depends on the cultivar and maturity at harvest. In general, the immature seeds have thinner and more tender hulls than the mature seeds (Stephens 1994a).

Although faba bean pods are usually harvested when the seeds have reached full size but are still green, they may also be harvested after the pods and seeds have dried (Anonymous 2002). For fresh consumption, the pods are usually harvested when the seeds are immature, at the milk stage, corresponding to a dry matter of 20–35% (Kmiecik et al. 2000; Lisiewska et al. 1999a, 1999b). In Europe, most of the faba bean is consumed fresh, at the milky stage (Eurostat 2006), but due to the high perishability of the seeds at this stage of maturity, most of the beans are used for canning or freezing (Kmiecik et al. 2000; Lisiewska et al. 1999a, 1999b). In other parts of the world, where faba beans are also cultivated, the seeds are most often harvested at the mature stage corresponding to a dry matter content of 40%, and subsequently dried to lower levels of moisture content (10–14%) in order to increase storability (Hossain and Mortuza 2006; Kmiecik et al. 2000; Lisiewska et al. 1999a; Shehata et al. 1984). Mature dry faba beans, like other legumes, have a higher yield and longer shelf life, as well as a higher protein (>25%) and mineral content than fresh immature faba beans (Barrat 1982; Hill-Cottingham 1983; Kmiecik et al. 1999; Lisiewska et al. 1999a, 1999b; De Simone et al. 1983; USDA 2006; Zee et al. 1988).

For fresh consumption, best quality faba bean pods should be shiny bright green and the seeds inside should be tender, creamy, and uniformly developed. Because the cotyledons are enveloped by an external hard hull, which hardens with increased maturity, faba beans are usually peeled before consumption. Compared to other types of beans, faba beans were described to have a bitter aftertaste, particularly when consumed without removing the hull (Anonymous 1998).

Fresh immature faba beans contain on average 70.4–72.6% water, 17.6–20.3% carbohydrates, 7–8% protein, 2.5% fiber, 3.7 mg of vitamin C, 333 IU of vitamin A, and 196 μg of β-carotene per 100 g of fresh fruit. Faba beans are also a good source of folate (148 μg/100 g fresh weight) (Barrado et al. 1994; Hossain and Mortuza 2006; USDA 2006). During the first stages of seed development sucrose content rapidly decreases from 15 to 4.0% on a dry weight basis, afterward decreasing slowly to 1.0% in the mature seed stage. Unripe green seeds have an average concentration of 2.0% glucose and sucrose, which decreases and disappears in ripe mature seeds (Lattanzio et al. 1986; Martin-Villa et al. 1982). Starch is found in large amounts in the seed, where it accounts for 41.4% and 47% of total dry weight in the whole seed and cotyledons, respectively. The hulls have almost no starch but have a very high content of fiber (53.4% of total dry weight) compared to the cotyledons (2.4% of total dry weight). However, protein and total sugar content is much higher in the cotyledons, accounting for 34.5 and 5.5% of the total dry weight, respectively, while the hulls contain 6.7 and 1.5% of protein and total sugars, respectively, on a dry weight basis. The lipid content of faba beans is low, approximately 1–2% of the dry weight. Apart from the high content of carbohydrates, protein, and B-group vitamins, faba beans are an important source of minerals such as calcium, magnesium, phosphorus, potassium, and sodium (Kmiecik et al. 2000).

The immature faba bean seeds are also a relatively good source of total phenolic compounds, particularly tannins (0.7–0.9% on a dry weight basis or 157 mg/100 g fresh weight), myricetin (26 mg/kg fresh weight), quercetin (20 mg/kg of fresh edible part), and kaempferal (less than

2 mg/kg fresh edible part) (Auger et al. 2004; Hertog et al. 1992; Hill-Cottingham 1983). Fresh faba beans also contain anthocyanindins such as delphinidin (0.05–0.56 mg/g fresh weight) and cyanidin (0.38–1.37 mg/g fresh weight) (Amarowicz and Pegg 2006).

Optimum Postharvest Handling Conditions

Faba beans should be stored at 0°C, and because pods and seeds lose moisture rapidly they should be stored with 90–95% relative humidity. When held under such conditions, expected postharvest life is about 1–2 weeks (Cantwell 2002). When relative humidity levels are >95%—for example, in consumer packages—temperatures above 7°C should be avoided, as serious decay may develop within a few days (Anonymous 2002).

Temperature Effects on Quality

Most of the published literature on the effects of environmental conditions on the storability or the compositional changes during storage of faba beans is in regard to the mature dry bean that is consumed, like other legumes, after soaking the seeds (De Simone et al. 1983; Lisiewska et al. 1999a). In addition, because fresh immature faba beans are very perishable, they are often canned or frozen immediately after harvest (Kmiecik et al. 2000; Lisiewska et al. 1999a, 1999b). For these reasons, as well as the limited economic importance of fresh immature faba beans (Hill-Cottingham 1983), no published scientific studies were found about the postharvest behavior or changes in the quality attributes of faba beans as affected by the postharvest environmental conditions.

Time and Temperature Effects on the Visual Quality of 'Primo' Faba Beans

'Primo' faba bean pods shown in Figures 6.1–6.10 were harvested at the immature green stage, with pods snapping easily when bent, and the seeds were at the milky stage of development, tender and not well developed. The pods were obtained from a commercial operation in the Orleans Island, Quebec, Canada, during the summer season (i.e., July). Promptly after harvest, fresh faba beans were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

External and internal visual quality attributes of 'Primo' faba beans harvested at the milk stage are affected by both storage time and temperature. Faba bean pods stored at 0°C maintain acceptable visual external quality during 13 days, with only very subtle signs of shriveling and dryness being noticeable at the extremities of the pod (Figure 6.1). However, after 12 days, turgidity decreases and the pods become softer, bending easily, compared to at harvest, where pods are very turgid and snap easily when bent. Internal quality of faba beans also remains acceptable during 12 days. But, as storage progresses, the velvety internal layer that protects the seeds loses moisture, and after 12 days some seeds show minor shriveling and a brownish discoloration (Figure 6.2).

When stored at 5°C, 'Primo' faba beans maintain acceptable external visual quality during 11 days. However, after 11 days the shell appears less bright green than at harvest, and the seeds show some minor signs of shriveling (Figure 6.3). By day 8, the pod is less firm than at harvest and bends easily without snapping. Internal visual quality evaluation shows that browning develops in some seeds after 4 days, and after 12 days the seeds appear less turgid than at harvest. The internal velvety liner that protects the seeds also appears less moist and thinner than at harvest (Figure 6.4).

After 10 days, the shell of 'Primo' faba beans stored at 10°C appears less bright green and slightly shriveled compared to at harvest, while the seeds appear shriveled, dry, hard, and dull after 11 days (Figure 6.5). After 6 days, the entire pod is soft and bends without snapping. Internal visual quality evaluation shows that after 7 days the smaller seeds become shriveled, dry, and hard. Shriveling affects all seeds after 9 days, and after 11 days the internal velvety liner that protects the seeds also appears drier and thinner than at harvest (Figure 6.6).

Color of 'Primo' faba beans changes from a bright green to a yellowish-green during storage at 15°C, and after 11 days the color of the pod appears more yellowish and less bright green than at harvest (Figure 6.7). Although not visible, firmness of the pod changes markedly from very turgid and firm, snapping easily at harvest, to a soft and flabby pod after 5 days. After 10 days, shriveling is somewhat perceptible at the extremities of the pod. Internal evaluation of the pod immediately after opening shows that after 3 days browning is noticeable in some seeds, and after 7 days the seeds appear shriveled, dry, and hard (Figure 6.8). After 11 days, the internal velvety liner that protects the seeds also appears less moist and downy, and much thinner than at harvest.

After only 3 days at 20°C, the middle parts of the pod show some dark brown discoloration, which spreads out to the whole pod as storage progresses. After 8 days, the entire surface of the pod is scattered with a blackish discoloration. Simultaneously, shriveling of the shell increases, and the seeds inside appear dry and hard (Figure 6.9). Shriveling of smaller seeds becomes evident after 2 days, and after 8 days all the seeds in the pod appear completely shriveled, very dry, and hard. Simultaneously, the velvety liner that envelops the seeds appears dry, rough, and much thinner than at harvest (Figure 6.10).

Overall, 'Primo' faba beans maintain better quality for longer periods of time when stored at 0°C (12 days) than at higher temperatures. Postharvest life of faba beans stored at 5, 10, 15, and 20°C is reduced to 8, 7, 5, and 2 days, respectively, mainly due to changes in the coloration and turgidity of the shell and seeds.

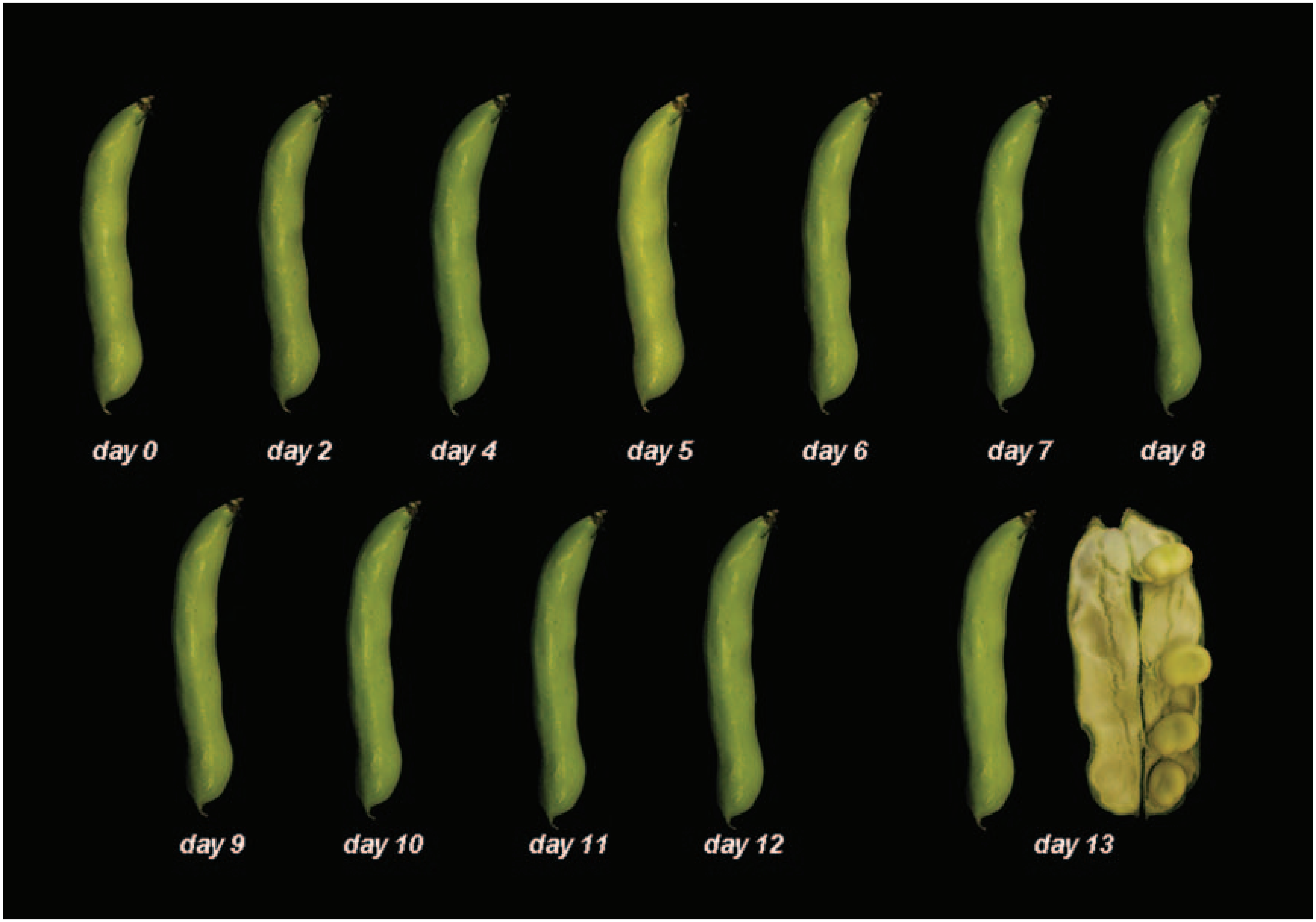
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Figure 6.1. Appearance of ‘Primo’ faba beans stored for 13 days at 0°C. Faba beans maintain acceptable external visual quality during 13 days.

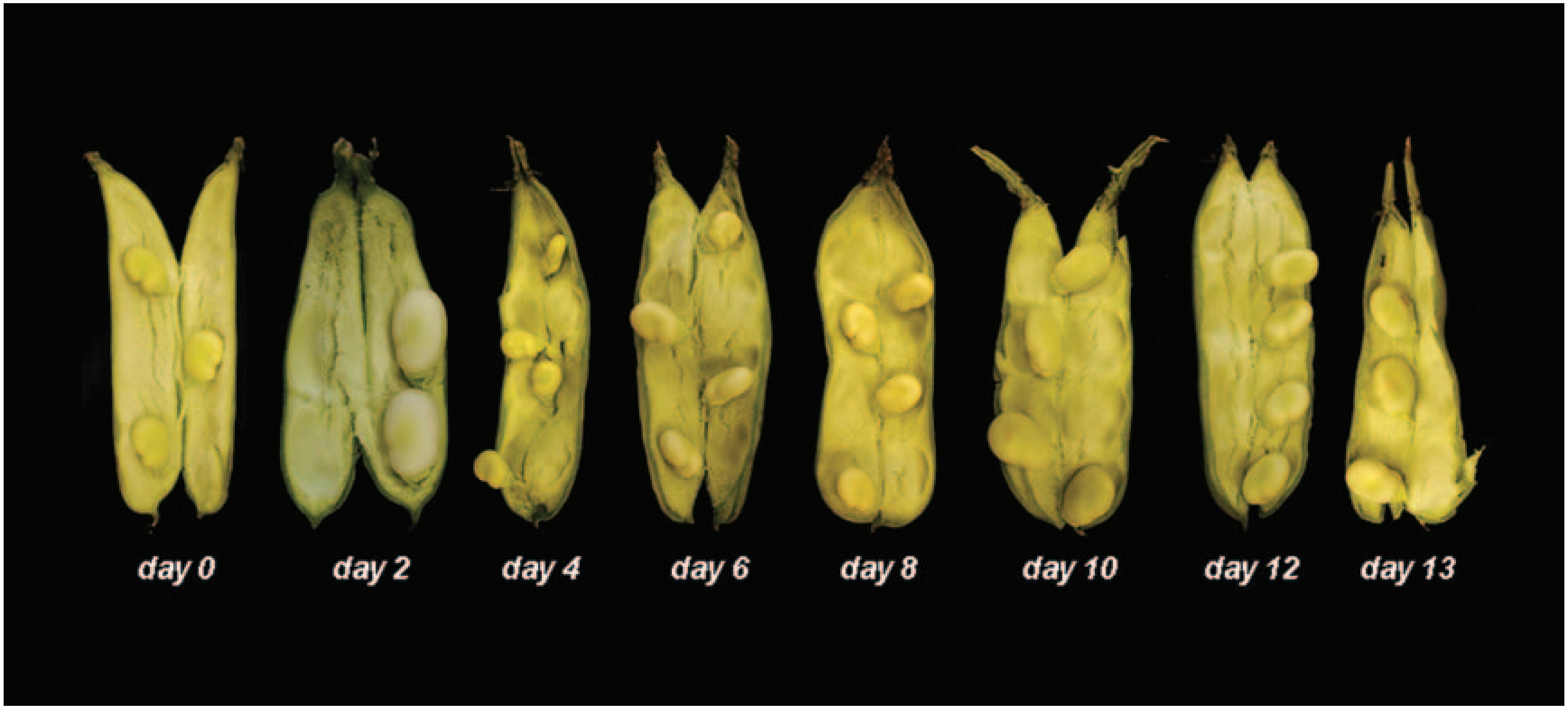
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Figure 6.2. Internal appearance of ‘Primo’ faba beans stored for 13 days at 0°C. After 13 days the seeds show minor signs of shriveling and discoloration.

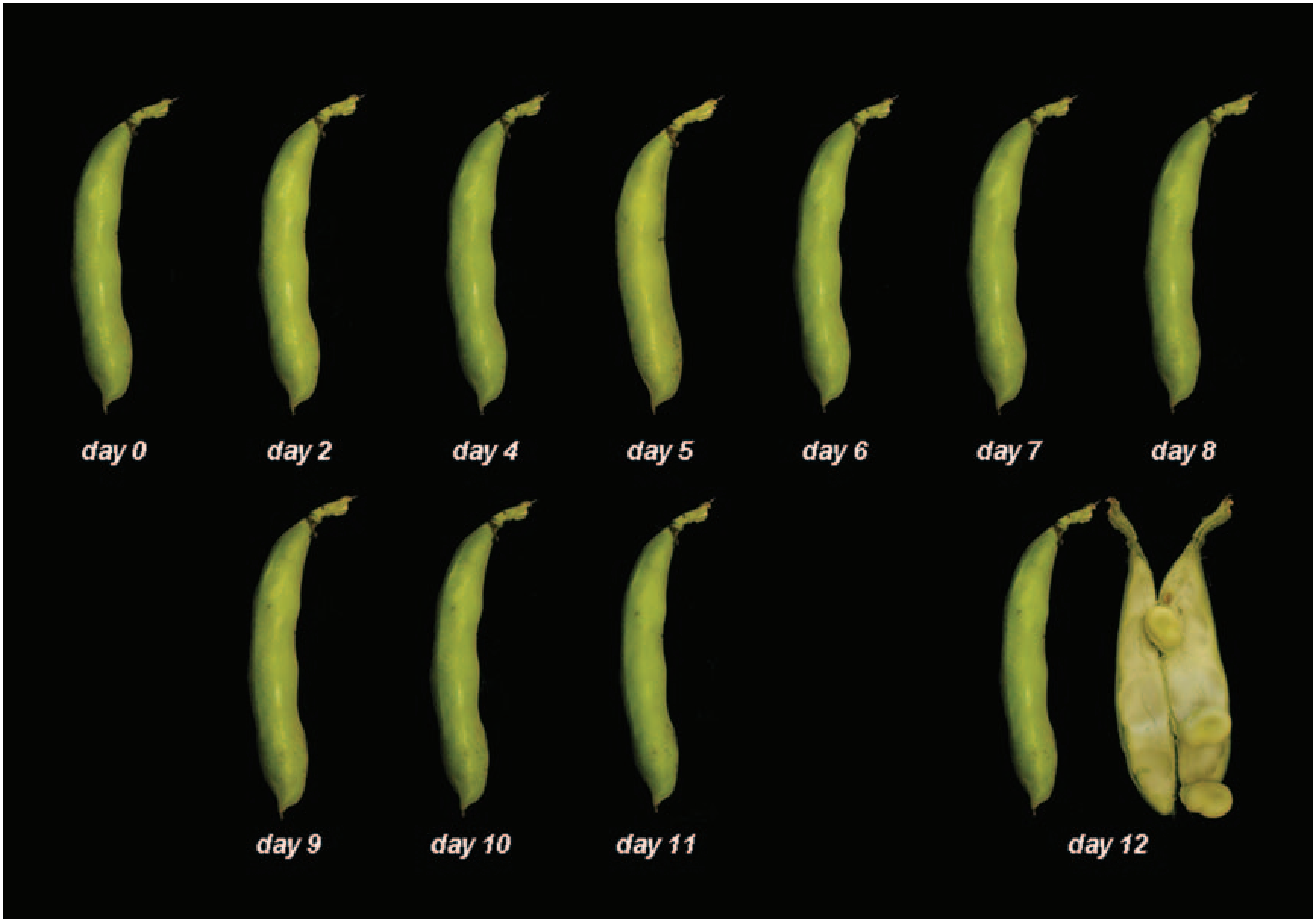
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Figure 6.3. Appearance of ‘Primo’ faba beans stored for 12 days at 5°C. Faba beans maintain acceptable external visual quality for 11 days.

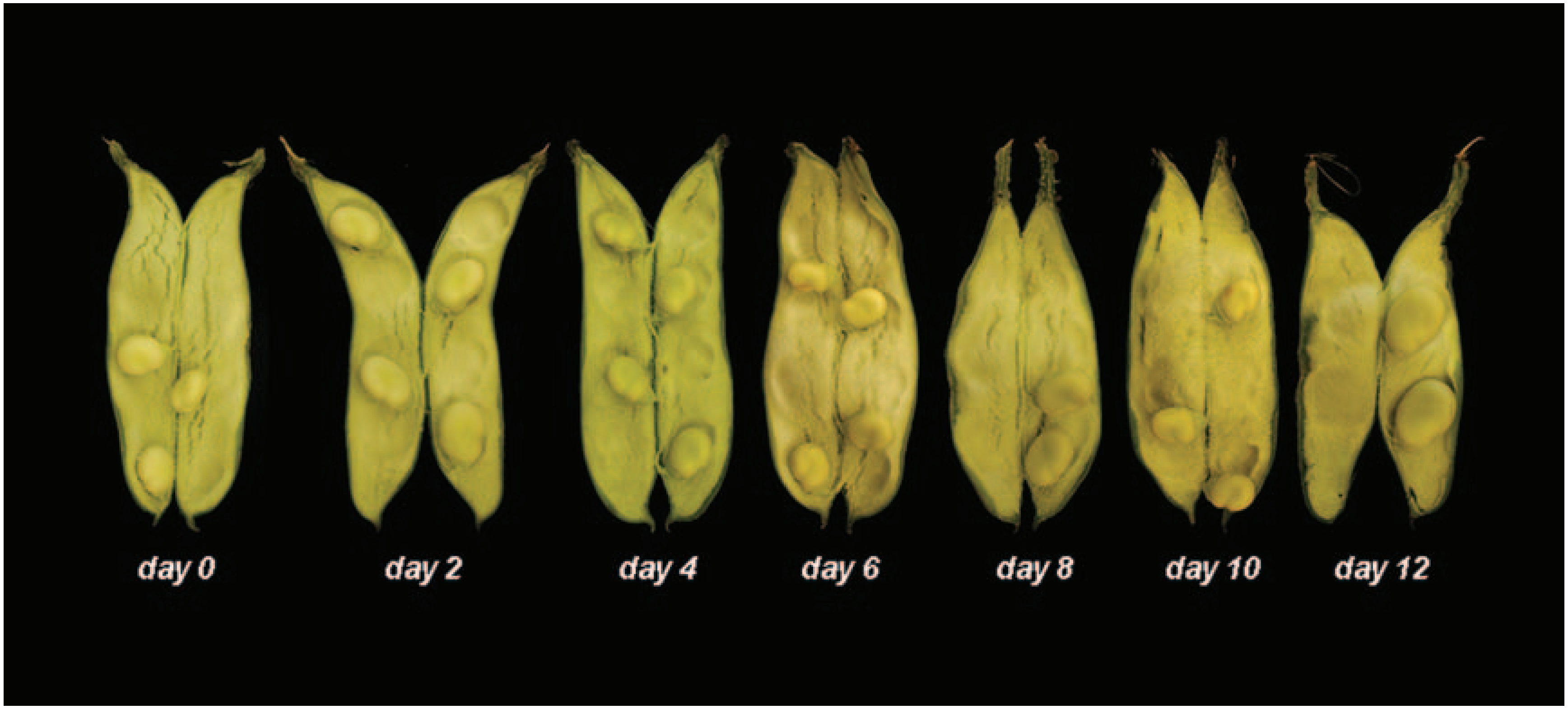
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Figure 6.4. Internal appearance of 'Primo' faba beans stored for 12 days at 5°C. Browning develops in some seeds after 4 days, and after 12 days the seeds appear less turgid than at harvest.

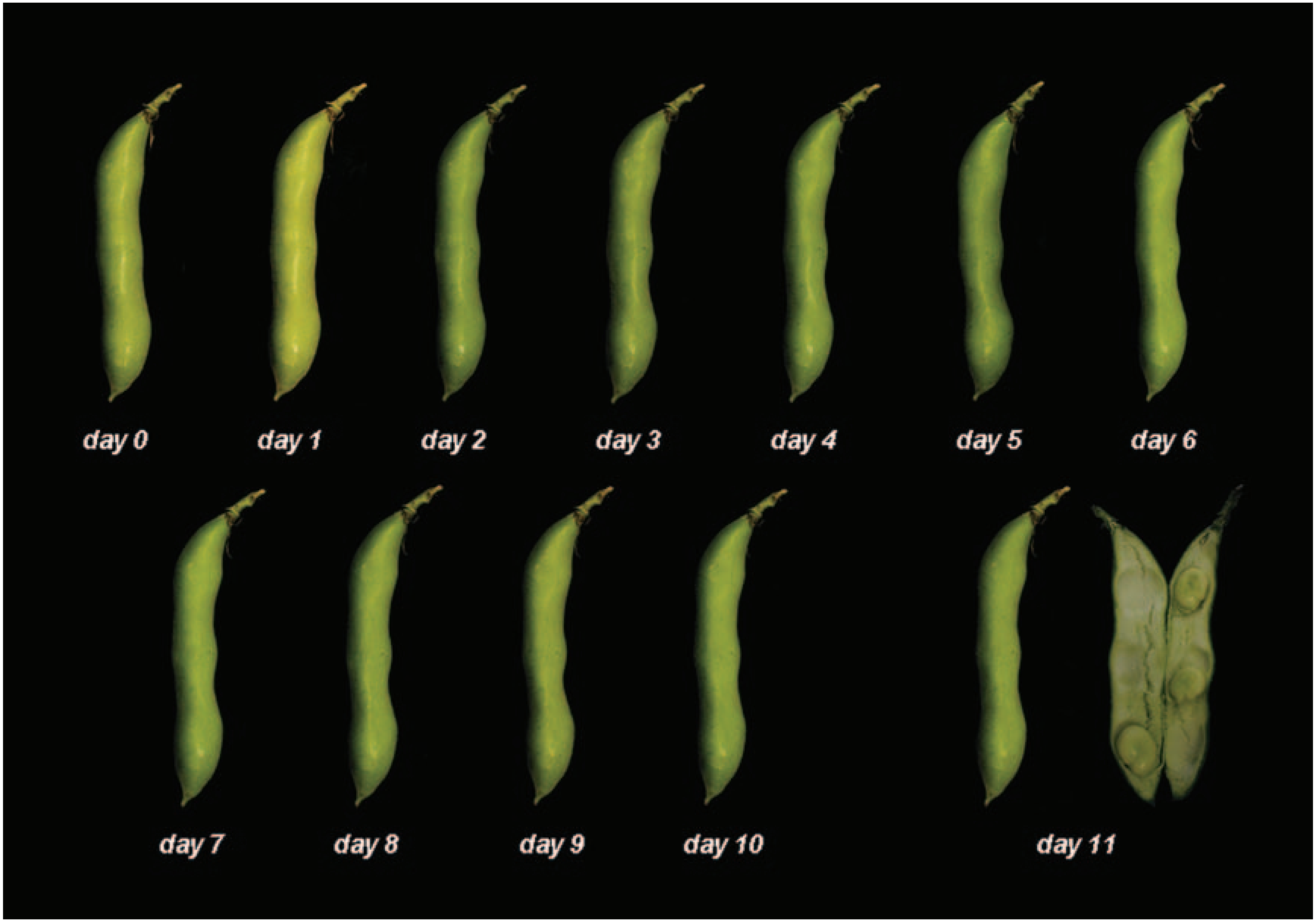
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Figure 6.5. Appearance of ‘Primo’ faba beans stored for 11 days at 10°C. After 10 days the shell appears less bright green and slightly shriveled compared to at harvest. The seeds appear dry, hard, and dull.

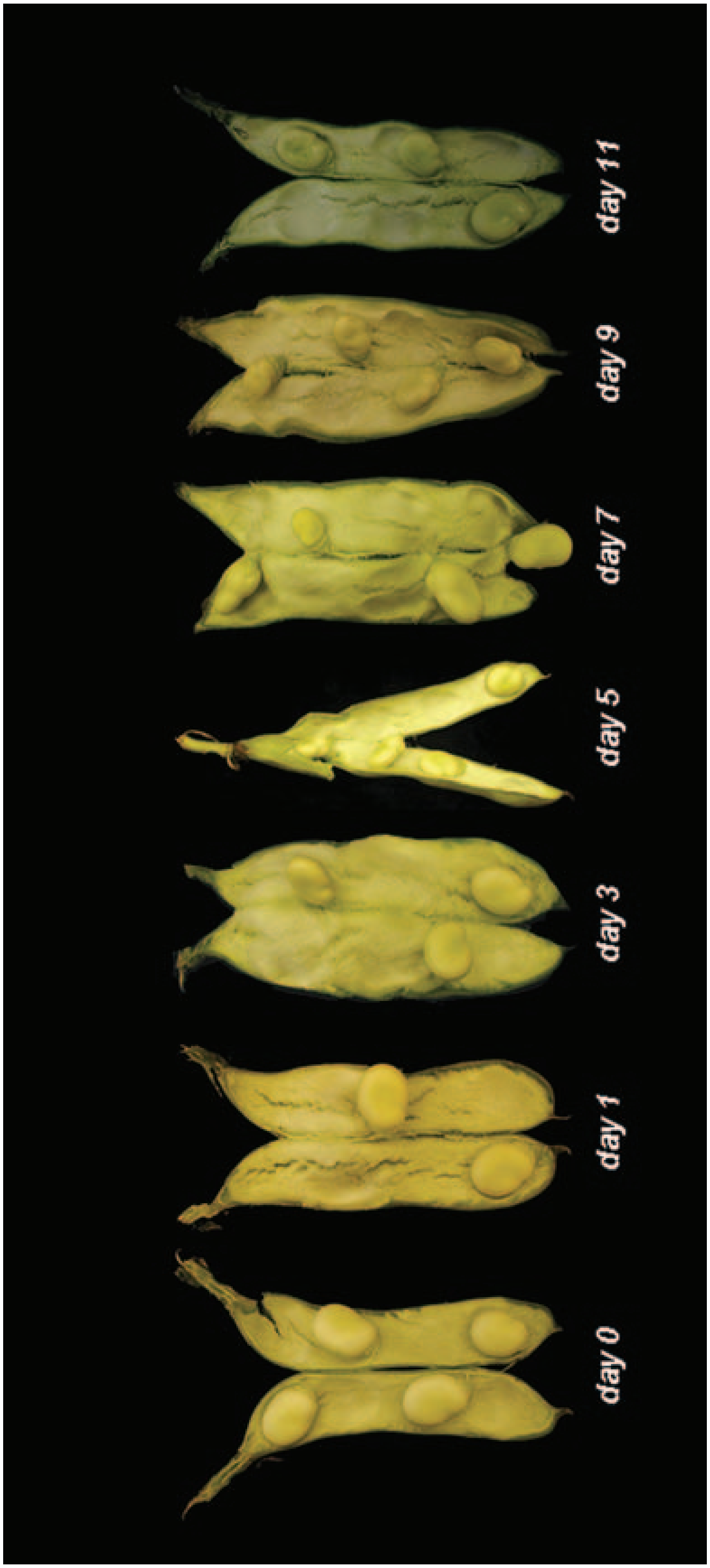
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Figure 6.6. Internal appearance of 'Primo' faba beans stored for 11 days at 10°C. After 9 days the seeds become dry and hard.

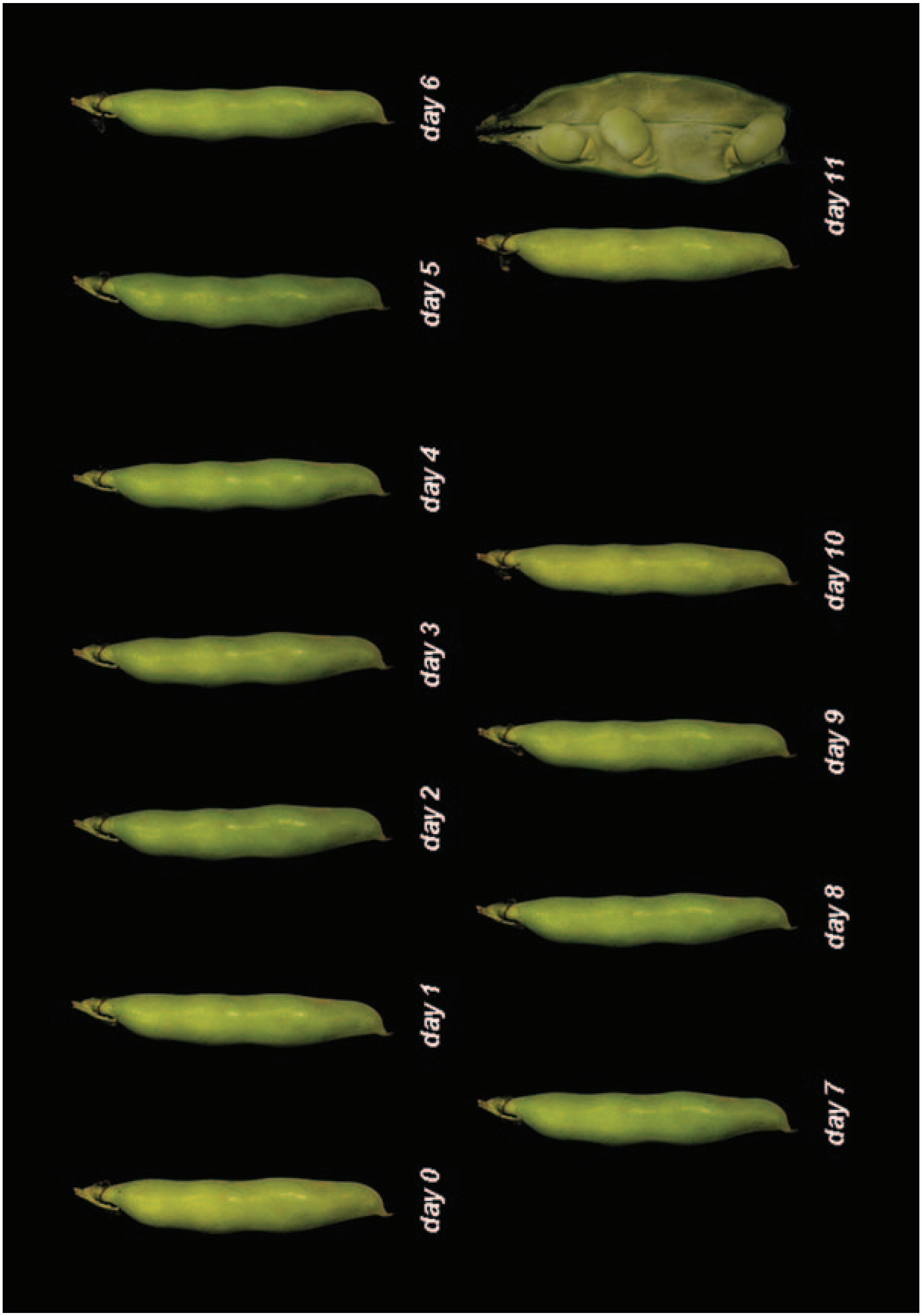
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Figure 6.7. Appearance of 'Primo' faba beans stored for 11 days at 15°C. After 10 days faba beans appear less turgid than at harvest.

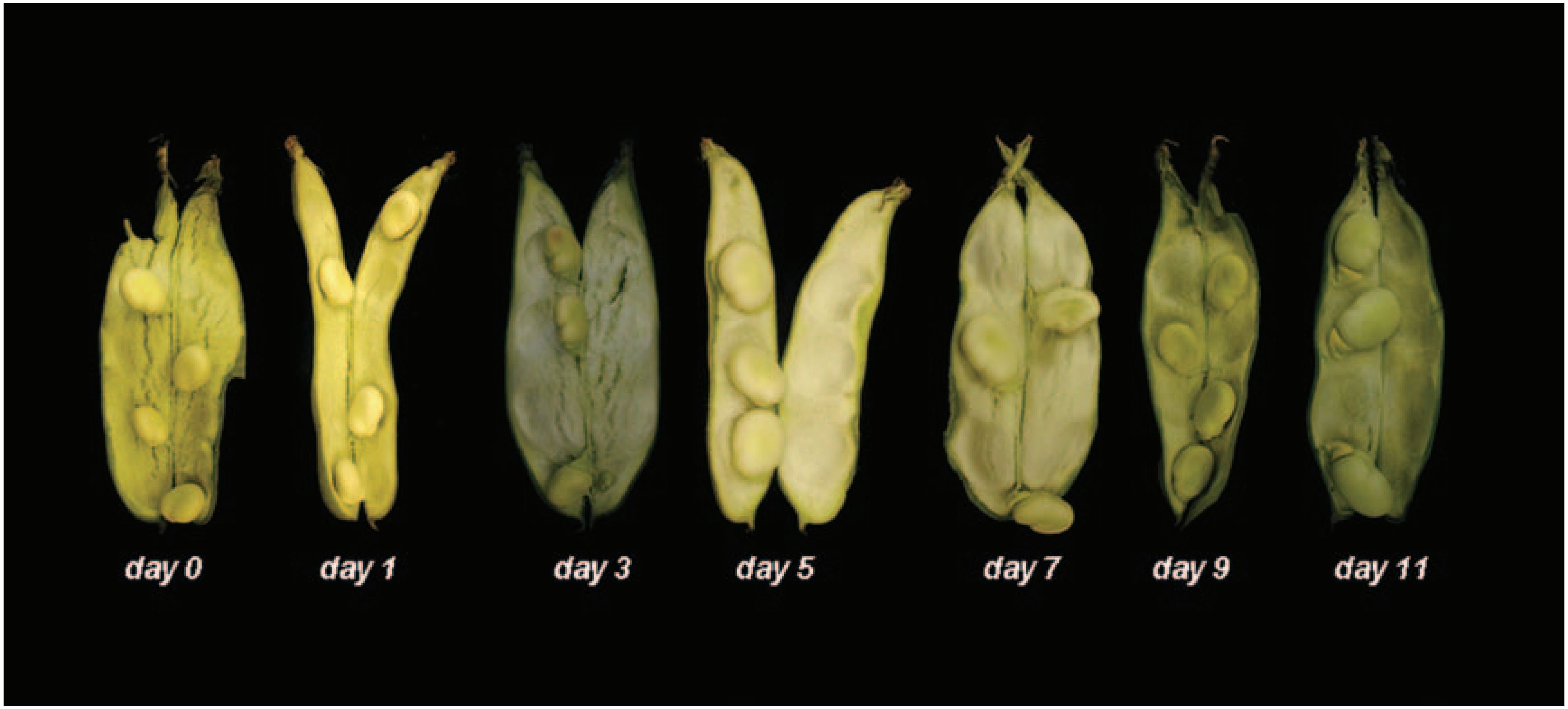
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Figure 6.8. Internal appearance of 'Primo' faba beans stored for 11 days at 15°C. After 3 days browning is noticeable in some seeds, and after 7 days the seeds appear dry and hard.

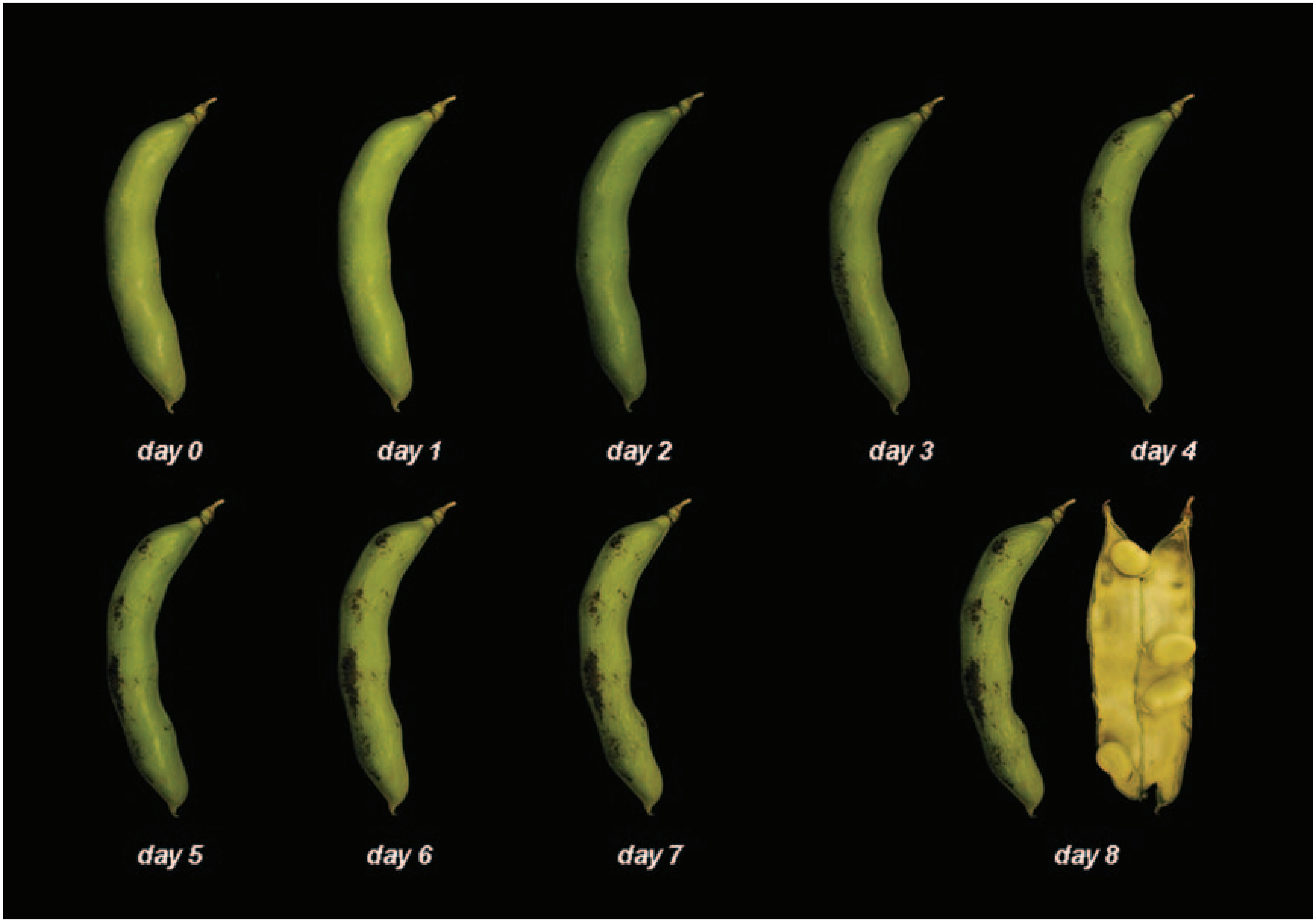
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Figure 6.9. Appearance of 'Primo' faba beans stored for 8 days at 20°C. After 3 days the pod shows some development of dark brown discoloration.

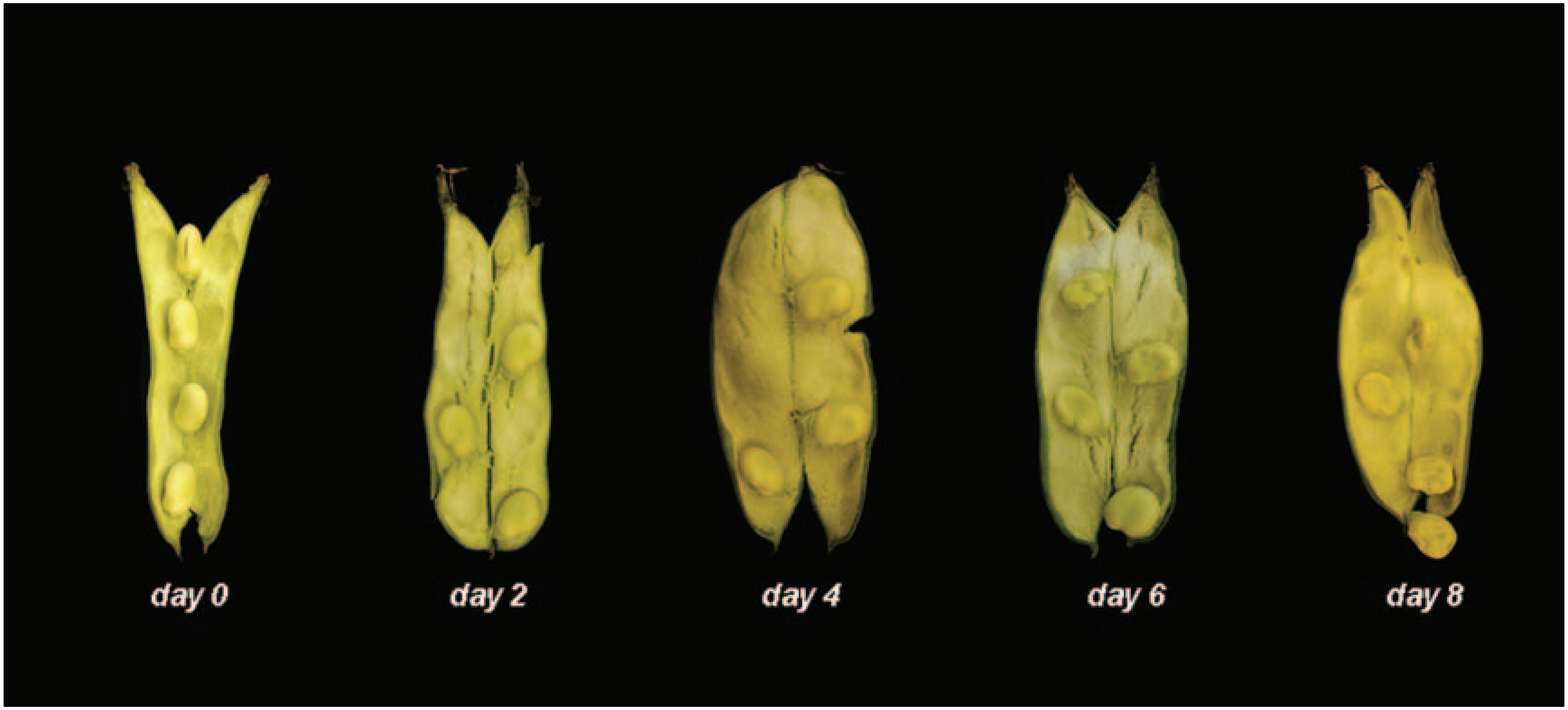


Figure 6.10. Internal appearance of ‘Primo’ faba beans stored for 8 days at 20°C. After 8 days the seeds and the velvety liner that protects the seeds appear dry, rough, and thinner.

SNAP BEAN

Scientific Name: *Phaseolus vulgaris* L.
Family: Fabaceae

Quality Characteristics

Snap beans are harvested at the immature stage, when tender and fleshy. Most snap beans for the fresh market grown on large fields are harvested mechanically, as hand-harvested is not considered cost-effective (Orzolek et al. 2002). However, mechanically harvested beans are more prone to develop browning on bruises and cuts or discoloration on broken ends than hand-harvested beans (Henderson and Buescher 1977; Sargent 1995).

Good quality snap beans should have a fresh appearance and bright green color and should be fleshy with small and tender green seeds. The entire pod should be tender but firm, snapping easily when bent, and should not be hard or fibrous. Fleshy, green, and tender snap beans have on average eight small green seeds. As the pod matures, the size of seeds increases and the beans become less tender and more fibrous (Watada and Morris 1967). Poor quality in snap beans is often associated with fibrousness due to overmaturity, broken beans due to rough handing, shriveling due to water loss, and chilling injury (CI) and decay due to exposure to inappropriate temperatures (Cantwell 2004).

As snap beans mature the moisture and chlorophyll contents decrease, while acidity and soluble solid contents increase. Due to the decrease in chlorophyll content, color of snap beans changes from a dark bright green (low L* and high a*) to light green (high L* and low a*) as they mature. Although color of snap beans is an important visual quality factor, in terms of consumer acceptance color was considered less important (2%) compared to fibrousness (33%), juiciness (31%), and firmness (19%). Thus, such observations suggest that the textural attributes are more important than color in the overall acceptance of snap beans (Martinéz et al. 1995).

Snap beans contain on average 90% water, 7% carbohydrates, 0.9% protein, 3% fiber, 12–16 mg of vitamin C, and 668 IU of vitamin A per 100 g of fresh weight, as well as other vitamins in minor concentrations (Favell 1998; Marlett and Vollendorf 1993; Proulx 2002; USDA 2006). Snap beans are also relatively rich in antioxidants and were classified in the top ten among other common vegetables in relation to antioxidant content and activity (Ou et al. 2002; Vinson et al. 1998). Total phenolic antioxidant content of snap beans averages 447 mg/kg of fresh weight contributing to a total phenol consumption of 4.2 mg/day based on a per capita consumption of 9.2 g of snap beans/day (Vinson et al. 1998).

Optimum Postharvest Handling Conditions

In order to remove field heat, avoid wilting, and extend postharvest life, snap beans should be immediately cooled after harvest. Hydro-cooling is recommended for dry climates where excessive loss of moisture may be detrimental for the quality of beans; otherwise, forced-air cooling is preferable, especially when beans are packed prior to cooling. Hydro-cooling may accelerate decay if the beans remain wet after cooling, whereas forced-air cooling may cause excessive water loss (Gorini et al. 1974; Sargent 1995). In general, forced-air cooled snap beans packed and transported in fiberboard boxes have lower weight loss and less shriveling and bruising than beans packed in wire-bound crates (Risse and Craig 1988).

For maximum postharvest life (i.e., 8–12 days), snap beans should be stored between 5 and 7.5°C with 95–100% humidity. When stored at 90–95% humidity and approximately 7°C snap beans will retain a good quality for about 7 days (Orzolek et al. 2002). Snap beans are injured when stored at temperatures below 5°C, and chilling damage such as opaque discoloration of the entire pod may occur after 7–8 days at this temperature. Depending on the cultivar and its susceptibility to CI, snap beans can be held for about 2 days at 1°C, 4 days at 2.5°C, and 6–10 days at 5°C before chilling symptoms become apparent. Storage at temperatures above 7.5°C results in increased yellowing, seed development, and loss of moisture (Cantwell 2004; Zong et al. 1992).

Postharvest life and quality of snap beans also depends on the combined effect of temperature and ethylene concentrations in the atmosphere. Ethylene concentrations above 0.005 µL/L combined with high storage temperatures will shorten the postharvest life of snap beans. Therefore, average concentration of ethylene found in boxes of green beans at the wholesale or retail level (0.17–1.17 µL/L) would contribute to a decrease in snap bean quality and reduced postharvest life (Wills and Kim 1996).

Temperature Effects on Quality

Postharvest temperature has a marked effect on the quality of snap beans, affecting not only the visual quality attributes such as color but also the texture and eating quality of the pods. Although superficial color intensity is dependent on the snap bean cultivar and the physiological maturity of the pod at harvest (Mayland and Dean 1971), increasing the storage time and temperature often results in loss of brightness and greenness, and increases yellowing. For example, at the time of harvest, 'Opus' snap beans were darker (lower L* value) and greener (higher hue value) than 'Leon' beans. L* value of 'Leon' snap beans showed a slight increase during storage at 0, 5, and 10°C, and after 7 days, snap beans stored at 0 and 5°C were more yellow (higher L* and lower hue) than those stored at 10°C for 2–5 days (Proulx 2002). After 8 days, snap beans stored at 10°C were lighter (higher L*) than pods stored at 5°C, but after 16 days lightness of the pods stored at 5°C increased significantly compared to days 4 and 8. After 16 days, hue and chroma of snap beans stored at either 5 or 10°C decreased significantly, indicating a loss of greenness and brightness of the pods (Trail et al. 1992).

When stored at temperatures lower than 5°C, snap beans may develop CI symptoms often characterized by changes in the visual quality attributes of the pod. General symptoms of CI in snap beans include opaque discoloration of the entire bean, surface pitting, russeting, brown elongated spots, and water loss (Cantwell 2004; Zong et al. 1992). In the temperature range of 5–7.5°C the most common symptom of CI is the appearance of isolated rusty brown spots. In general, CI symptoms aggravate with exposure time to chilling temperatures, and when the beans are transferred to ambient temperatures, often result in loss of the entire pod (Proulx 2002; Zong et al. 1992). For example, yard-long beans stored at chilling temperatures developed russet spotting and regularly distributed elongated brown spots that were aggravated after transfer to 15°C, resulting in a complete deterioration of the affected tissue, watery appearance of the pods, and increased decay (Zong et al. 1992). Beans stored at 0 or 3°C for 10 days developed CI pitting that showed deterioration of the epidermal and first layer of hypodermal cells and was later invaded by fungi, while pit-free tissue maintained its characteristic structure (Burzo et al. 1994). After 3 and 7 days of storage, pitting appeared clearly on pods stored at 0 or 5°C, respectively, and symptoms increased upon transfer to ambient temperature. Overall quality was further decreased by development of decay (Abou Aziz et al. 1976). Snap bean cultivars stored continuously at 5°C developed black tips and poor appearance. However, upon transfer to 15°C after 14 days at 5°C, quality declined greatly, pitting and diagonal brown streaks became severe, and some soft rot developed. The rate of deterioration, which was initially slow at the beginning of chilling storage, accelerated significantly as soon as CI symptoms developed (Watada and Morris 1966b). Groeschel et al. (1966) also reported that when green beans were stored at temperatures below 7°C and then transferred to room temperature at 21°C, russeting generally developed on the beans within 1 day.

Snap bean cultivars differ significantly in their susceptibility to CI (Abou Aziz et al. 1976; Gorini et al. 1974; Watada and Morris 1966a, 1966b). For example, Gorini et al. (1974) reported a variation in the percentage of CI incidence in seventeen different snap bean cultivars ranging from 0 to 42.5% when stored for 7 days at 4°C, and from 0 to 48.5% when stored at 7°C for the same period of time. Furthermore, the same authors concluded that due to CI some cultivars can only be stored for 2 days, while others can be stored for 7 days. In another study, 'Romano' snap beans were only slightly affected by a 14-day storage period at 5°C, as after transfer to 15°C their postharvest life was reduced by only 3%, while postharvest life of 'Top Crop' and 'Tendergreen' snap beans was reduced by 40% due to CI. Yet the snap bean cultivars most affected by CI with a 60% reduction in their postharvest life, after transfer to 15°C, were 'Contender' and 'Kentucky Wonder 191' (Watada and Morris 1966a). Likewise, while 'Opus' snap beans showed no signs of pitting after storage for 6 days at 5°C, after 6 days pitting reached objectionable levels in 'Leon' snap beans stored under the same conditions. Nonetheless, no pitting was observed in snap beans from both cultivars stored at 10, 15, or 20°C (Proulx 2002). 'Amboy' beans stored at 10°C did not show any signs of chilling damage compared to storage at 0 or 3°C, nor any symptoms of physiological disorders of degradation of cell ultrastucture (Burzo et al. 1994).

Browning or broken-end discoloration similar to that observed in snap beans stored at chilling temperatures may also occur as a result of injuries caused during harvest, or when beans are held at ambient or under fluctuating temperatures (Henderson et al. 1977; Nunes et al. 2001). Snap bean cultivars stored at 15°C developed symptoms of senescence after approximately 18–29 days, depending on the cultivar (Watada and Morris 1966b). During storage the color of snap beans faded, the surface became leathery with slight and small depressions, flexibility increased, and the tips became discolored. Some pods developed purple blemishes as the color faded and others developed diagonal brown streaks. As the pod became yellow, the endocarp began to collapse and internal cavities formed. The quality declined more rapidly at the beginning of storage than later on, and after approximately 10–12 days at 15°C quality of 'Top Crop,' 'Romano,' 'Tendergreen,' and 'Blue Lake' snap bean cultivars was considered fair (Watada and Morris 1966b). Rate of deterioration of green snap beans was lower at 10°C compared to storage at 20°C, and wilting, shriveling, and yellowing were the main causes of deterioration for pods stored either at 10 or 20°C (Abou Aziz et al. 1976). After 24 hours at 27°C, intentionally bruised beans were markedly discolored (Henderson et al. 1977), and when exposed to fluctuating temperature (from 4 to 23°C) browning significantly increased when compared to beans held at constant temperatures (Nunes et al. 2001). Increase in browning was associated with increased soluble phenolic content, which increased 70% above initial levels in broken pods (Henderson et al. 1977).

Temperature and storage time also have a significant impact on textural changes and softening of snap beans. After storage, 'Leon' and 'Opus' snap beans had harder seeds, and the pods were softer and bent more easily without snapping than freshly harvested beans. 'Leon' snap beans stored at 0, 5, and 10°C reached objectionable softness after only 3 days of storage, yet pods stored at 0°C appeared softer than those stored at 5 or 10°C. Increased softening and loss of turgidity in 'Leon' beans stored at 0°C might have resulted from the chilling damage induced in the beans stored at this temperature (Proulx 2002).

Parallel with softening, shriveling severity in 'Opus' snap beans increased with increasing temperature. However, after 4 days, shriveling symptoms were more important in pods stored at 0°C than at 5 or 10°C. Accelerated softening and increased shriveling observed in beans stored at 0°C compared to the other temperatures might have resulted from greater sensitivity of 'Leon' to chilling temperatures than the 'Opus' cultivar (Proulx 2002). Loss of turgidity and crispness of snap bean pods may also be due to the loss of water and increased soluble pectin (Sistrunk et al. 1989). In fact, weight loss of 'Opus' and 'Leon' snap beans increased with storage time and temperature, and according to Robinson et al. (1975), snap beans were considered unacceptable for sale when weight loss attained 5% of the initial weight of the pods, due to loss of moisture.

Weight loss in snap beans can be significantly reduced by the use of protective packaging during handling and distribution (Buescher and Adams 1979; Trail et al. 1992). For example, weight loss of snap beans packed in perforated bags attained 6.5% after 7 days at 7°C, compared to a weight loss of 37.7% observed in snap beans packed in open pans and stored at the same temperature (Buescher and Adams 1979). Likewise, a maximum weight loss of 2.6% after 16 days at 10°C was reported for snap beans packed in plastic films (Trail et al. 1992). The rate of weight loss in snap beans was also reported to be dependent on the cultivar and the precooling method used (Gorini et al. 1974; Proulx 2002). For example, the rate of weight loss was more rapid in 'Leon' than in 'Opus' snap beans. After 2 days at 20°C, 'Opus' had lost 12.6% of its initial weight while 'Leon' lost 19.7% (Proulx 2002). In seventeen different snap bean cultivars weight loss ranged from 9.4 to 27.17% in hydro-cooled snap beans stored at 4°C for 7 days, compared to a weight loss of 12.06–32.73% in air-cooled snap beans (Gorini et al. 1974). After 3 days, 'Leon' beans showed a slightly greater loss of weight at 5°C than at 10°C, which was maintained throughout storage. This point corresponded to the time that CI symptoms (i.e., pitting) started to be evident in beans stored at 5°C (Proulx 2002). In fact, exposure of snap beans to chilling temperatures (i.e., 0 or 5°C) might have resulted in loss of cell membrane integrity and leakage of solutes and water, which often leads to manifestation of CI symptoms such as pitting and wilting (Kays 1991).

At the time of harvest, pH of 'Opus' and 'Leon' snap beans was approximately 6.4, and the values were not significantly affected by storage time and temperature (Groeschel et al. 1966; Proulx 2002). The acidity of snap beans at harvest was quite similar, 0.09% of malic acid for 'Opus' and 0.08 % of malic acid for 'Leon,' but in general, acidity significantly decreased, regardless of the storage temperature (Burzo et al. 1994; Proulx 2002). However, acidity of cellular sap was greater in beans exposed to 0 or 3°C than those exposed at 10°C (Burzo et al. 1994). Compared to initial values, after 2 days at 20°C, there was a reduction of approximately 45% and 50% in the acidity of 'Opus' and 'Leon,' respectively. At 10°C, there was a large difference in the rate of acidity reduction in 'Opus' snap beans (48% reduction) compared to 'Leon' (56% reduction). At 0 and 5°C 'Opus' and 'Leon' beans showed an acidity reduction of approximately 43% and 53% at 0°C and 5°C, respectively (Proulx 2002).

At the time of harvest, the soluble solids content of snap beans was approximately 4.5–5.0% (Proulx 2002; Trail et al. 1992). However, after 2 days at 20°C, both 'Opus' and 'Leon' snap bean cultivars showed a reduction of approximately 52% of their initial soluble solids content. Decline in the soluble solids content of beans stored at 0, 5, and 10°C followed the same trend for both cultivars. However, decrease in the soluble solids content was more important in 'Leon' when compared to 'Opus' beans. At the end of the 7-day storage period, 'Leon' and 'Opus' snap beans stored at 5°C showed a reduction of 58 and 51% in their initial soluble solid contents, respectively (Proulx 2002). A significant decrease in the soluble solids content of snap beans was also observed after 8–16 days at 5°C compared to 4 days at the same temperature (Trail et al. 1992). Total sugar content of snap beans stored at 8°C initially increased, but a decrease was observed subsequently, when storage was extended to 18 days. The hydrolysis of starch to release soluble sugars and the possible synthesis of some sugars that occurred during the first days of storage may explain the initial increase in sugar content of snap beans stored at 8°C. Subsequently, the drop in the sugar content observed after 11 days at 8°C might be related either to an increase in the respiration metabolism, which involves the consumption of simple sugars, or to the condensation of sugars. Sucrose content of snap beans increased during storage at 8°C, while fructose and glucose decreased (Sánchez-Mata et al. 2003).

Loss of ascorbic acid increased, as storage time and temperature increased, and was greatly affected by the environmental conditions during distribution from the field to home (Cámara et al. 1997; Favell 1998; Howard et al. 1999; Proulx 2002; Trail et al. 1992; Wu et al. 1992). For example, ascorbic acid content of green beans significantly decreased during simulated distribution from approximately 17 mg/100 g at the time of harvest to 6.2 mg/100 g fresh weight after simulated distribution (6 hours at 20–25°C, 3 days refrigerated transport at 4°C, followed by 12 days display at 10–16°C, and 3 days home refrigerator storage at

4°C). About 58% of the initial ascorbic acid content of green beans was, however, lost during the first 3 days of refrigeration at 4°C, due most likely to an accelerated enzymatic and non-enzymatic degradation (Wu et al. 1992). Likewise, initial content of ascorbic acid of 'Blue Lake' green beans was reduced by more than 70% after storage for 1 week at 4°C. After 16 days at 4°C, the initial concentration of ascorbic acid (15.2 mg/100 g fresh weight) of 'Blue Lake' beans was reduced to 1.3 mg/100 g fresh weight (Howard et al. 1999). Although ascorbic acid was initially well retained in green beans stored at 4°C, it dropped afterward to a level below that observed in green beans stored at 20°C. After only 1 day at ambient temperature, 30% of the ascorbic acid content of snap beans was lost (Favell 1998), while after the same period of time 'Opus' and 'Leon' lost 44% and 55% of their initial ascorbic acid content (Proulx 2002). After 3 days of storage, 'Leon' snap beans stored at 5°C showed the larger decrease in ascorbic acid content when compared to beans stored at 10°C. This decrease was coincident with the development of the first CI symptoms (Proulx 2002). CI often causes accelerated losses in the ascorbic acid content on chilling-sensitive crops such as snap beans. In fact, the rate of ascorbic acid loss per day was higher in green beans stored at 4°C (10.8%) than at 20°C (7.8%) (Favell 1998). In 'Provider' and 'Strike' green beans stored for 2 or 3 weeks at 2°C, ascorbic acid content decreased by 75% or 90%, respectively, compared to initial values (Albrecht et al. 1991).

Conditions favorable to water loss after harvest have been reported to result in a rapid loss of ascorbic acid (Lee and Kader 2000; Nunes et al. 1998). Ascorbic acid may be rapidly oxidized as a consequence of tissue damage like that occurring in snap beans due to CI, which may lead to increased water loss and allow exposure of ascorbic acid to oxidation. Besides, ascorbate oxidase, normally bound to the cell walls, might be released following tissue damage or water loss. Therefore, water loss combined with tissue damage due to exposure to chilling temperatures may contribute to increased loss in ascorbic acid content in snap beans (Nunes et al. 1998). Although no signs of CI were observed in flat green beans after storage at 8°C for 18 days, ascorbic acid levels decreased with storage time from initial values of 2.4 mg/100 g fresh weight at harvest to approximately 1.2 mg/100 g fresh weight after storage. Likewise, levels of other vitamins such as thiamine (vitamin B1), riboflavin (vitamin B2), and pyridoxine (vitamin B6) were also influenced by storage time, as they significantly decreased after storage of flat green beans for 11–18 days at 8°C (Cámara et al. 1997).

Reduction in chlorophyll content of snap beans often results in yellowing of the pods, poor appearance, and reduced postharvest life. Changes in chlorophyll pigments during storage of green beans are related to synthesis and degradation processes and depend on the maturity stage and on the environmental conditions during the postharvest period (Monreal et al. 1999; Proulx 2002). Storing snap beans at 5°C for 16 days had no major effect on the chlorophyll content, probably because temperature was low enough to slow down chlorophyll degradation. On snap beans stored at 10°C, chlorophyll content increased after 4 days but then dropped after 8–12 days of storage to the levels observed at harvest. Although chlorophyll content increased during a short 4-day storage period at 10°C, longer exposure times led to significant reduction in the chlorophyll levels of snap beans (Trail et al. 1992). In green beans stored at 20°C, chlorophyll content decreased by 56% after 20 days. Likewise, storage of green beans at 4, 8, or 12°C for 15 days, followed by transfer to 20°C, resulted in a reduction of chlorophyll content of about 33–47% compared to initial values (Monreal et al. 1999), while snap beans stored at 7°C followed by transfer to 20°C retained 68% of their initial chlorophyll content (Groeschel et al. 1966). Although storage of 'Perona' green beans at 8°C resulted in an increase of chlorophyll content during the first 13 days of storage, a significant decrease was observed afterward. Besides, transfer of green beans to 20°C for 2 additional days after holding for 6 days at 8°C resulted in accelerated chlorophyll synthesis, whereas green beans stored for 13 or 14 days under the same conditions showed a decrease in chlorophyll after transfer (Cano et al. 1998). The greatest chlorophyll reduction was observed in green beans stored at 4°C after 15 days of storage (Monreal et al. 1999). Storage at high temperatures may affect the respiration rate of the tissue and accelerate the degradative process while chilling temperatures (below 7°C) can result in increased pigment degradation due to chilling damage (Montreal et al. 1999). Chlorophyll content of the 'Leon' and 'Opus' snap beans decreased continuously during storage. After 2 days at 20°C, 'Opus' snap beans had lost 53% of their initial chlorophyll content, while chlorophyll content of 'Leon' was decreased by 57%. In snap beans stored at 0 and 5°C, chlorophyll content decreased during the first 4 days of storage, but after that time it tended to stabilize. After 5 days at 0, 5, and 10°C, chlorophyll content of 'Opus' snap beans decreased by 44%, 41%, and 54%, respectively, compared to initial values at harvest. After the same period of time, chlorophyll content of 'Leon' snap bean stored at the same temperatures decreased by 59%, 57%, and 56%. Chlorophyll degradation was more important in snap beans exposed to chilling temperatures compared to those exposed at nonchilling temperatures (Prouxl 2002). In effect, it has been suggested that CI can induce severe damage in the chloroplast membranes and accelerate the degradative pathways of pigments, resulting in loss of chlorophyll content (Monreal et al. 1999).

Lutein, one of the most abundant pigments of snap beans, did not change during storage for 15 days at 8°C, while in beans stored at 12 and 4°C a slight decrease in lutein content was observed. Although transfer of green beans to 20°C resulted in an initial increase in lutein content during the first 7 days of storage, an 80% degradation of the pigment was observed after 17 days of storage. Likewise, β-carotene content of green beans did not significantly change during storage at 8°C for 15 days, while it significantly decreased in beans stored at 4 or 12°C (Monreal et al. 1999). In a simulation of green bean distribution from the field to home (6 hours at 20–25°C plus 3 days of refrigerated transport at 4°C, followed by 12 days of display at 10–16°C and 3 days of home refrigerator storage at 4°C), β-carotene content of green beans did not change significantly (Wu et al. 1992). However, in another study β-carotene content of ‘Perona’ green beans stored at 8°C increased by 40% after 18 days of storage compared to initial values. In addition, transfer to 20°C also produced a significant acceleration in the synthesis of β-carotene (Cano et al. 1998). On the other hand, β-carotene content of ‘Blue Lake’ was significantly reduced during refrigerated storage, as a decrease from 183 IU/100 g fresh weight at the time of harvest to 164 IU/100 g fresh weight after at 4°C for 16 days was observed (Howard et al. 1999).

Time and Temperature Effects on the Visual Quality of ‘Opus’ Snap Bean

‘Opus’ snap beans shown in Figures 6.11–6.16 were harvested at the bright green and fleshy stage with small green seeds. The pods were obtained from a commercial operation in Homestead, Florida, during the winter season (i.e., February–March). Promptly after harvest, fresh beans were stored at five different temperatures (1.0 ± 0.3°C, 5.0 ± 0.2°C, 9.4 ± 0.4°C, 14.40 ± 0.4°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Postharvest changes in the visual quality attributes of ‘Opus’ snap beans are mainly related to changes in coloration, shriveling, and loss of firmness. Snap beans stored at 1°C maintain acceptable visual quality during 6 days (Figure 6.11). However, after 4 days the pods are soft and bend easily without snapping. After transfer to 20°C for 1 additional day, snap beans stored for 3 days at 1°C show symptoms of CI such as pitting and russet spotting (Figure 6.12).

‘Opus’ beans stored at 5°C maintain acceptable visual appearance for 4 days (Figure 6.13). Although shriveling and dryness are only noticeable at the tip of the pod after 6 days of storage, firmness becomes objectionable after approximately 4 days and reduces the postharvest life of the beans. No signs of CI were observed in ‘Opus’ snap beans stored at 5°C upon transfer to nonchilling temperature. Likewise, no signs of CI were observed in ‘Opus’ snap beans stored at 10°C for 4 days, after transfer to 20°C for 1 additional day. ‘Opus’ snap beans stored at 10°C maintain acceptable visual appearance during 3 days (Figure 6.14). After 3 days, shriveling becomes evident at the tip and the bean pod appears less green than at harvest. Firmness decreases during storage and after only 2 days the beans become softer, bending easily without snapping.

‘Opus’ snap beans show objectionable quality after only 2 days at 15°C (Figure 6.15). Yet, after only 1 day firmness is significantly decreased and the beans become very soft and rubbery, bending very easily without snapping. After 3 days, the edges of the beans appear very dry and shriveled due to loss of moisture.

Shriveling, dryness, and loss of turgidity occur rapidly in ‘Opus’ snap beans stored at 20°C. After only 1 day, signs of shriveling are already noticeable, and after 3 days the entire pod appears dry, extremely soft, and shriveled (Figure 6.16).

Quality deterioration of ‘Opus’ snap beans is very fast following harvest mainly due to the development of CI symptoms, loss of turgidity, and shriveling. Maximum postharvest life is obtained when ‘Opus’ snap beans are stored at 5°C (4 days), while visual quality remains acceptable for only 3 days at 1 and 10°C, and for 2 and 1 days when stored at 15 and 20°C, respectively.

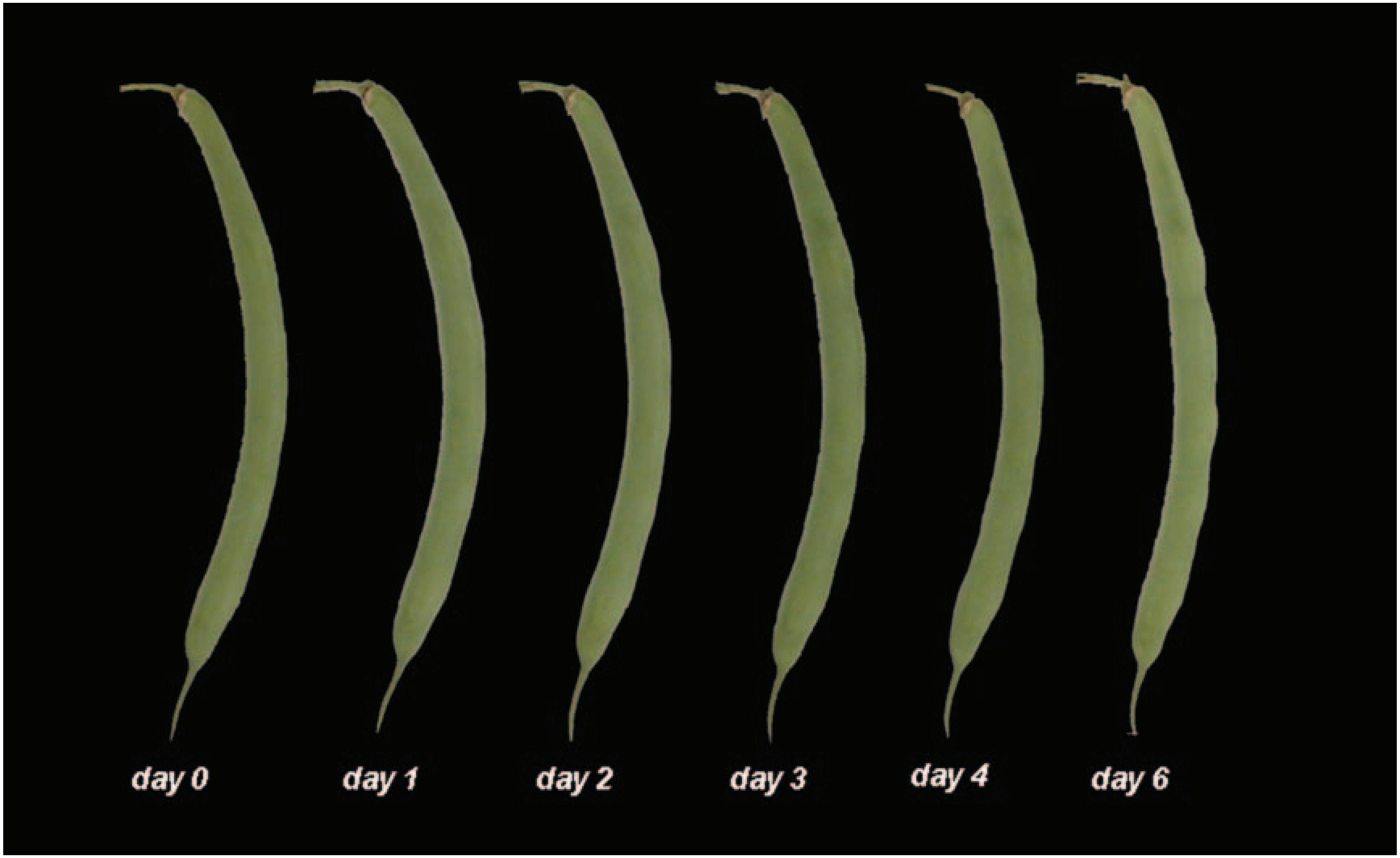

day 0
day 1
day 2
day 3
day 4
day 6

Figure 6.11. Appearance of 'Opus' snap beans stored for 6 days at 1°C. Snap beans maintain acceptable visual quality during 6 days.

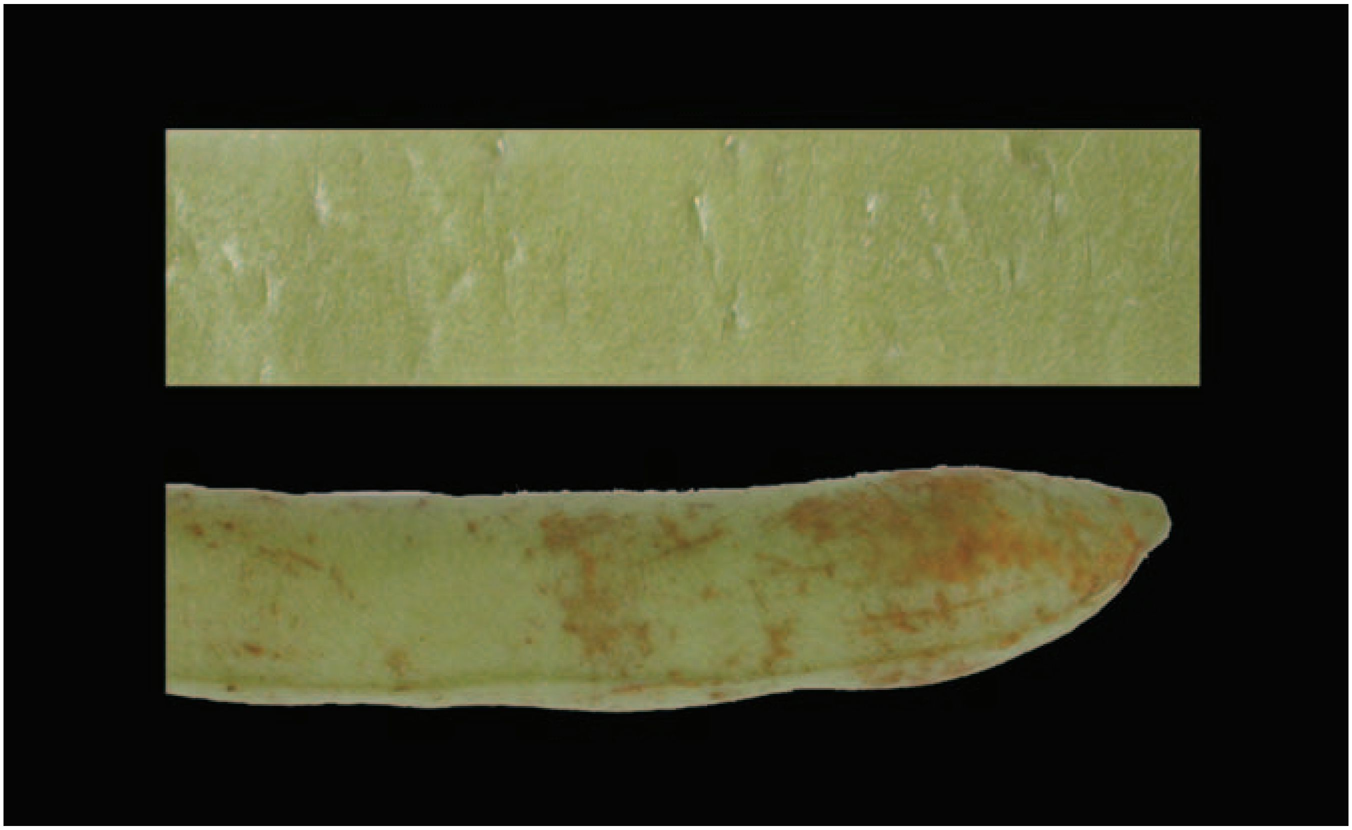
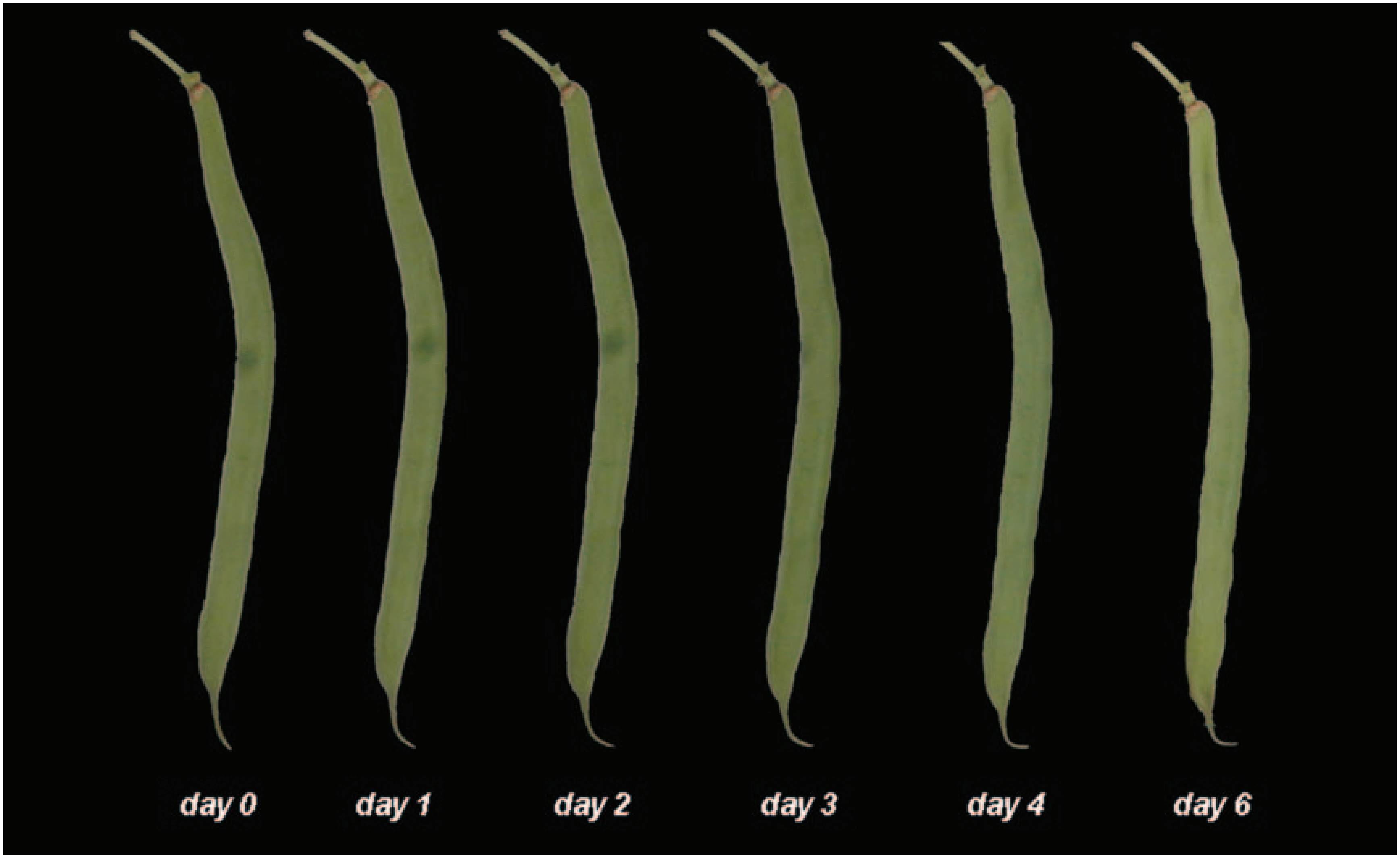


Figure 6.12. Pitting (above) and russet spotting (below) in 'Opus' snap beans after 3 days at 0°C plus 1 day at 20°C.


day 0
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day 6

Figure 6.13. Appearance of ‘Opus’ snap beans stored for 6 days at 5°C. Snap beans maintain acceptable visual quality during 4 days.

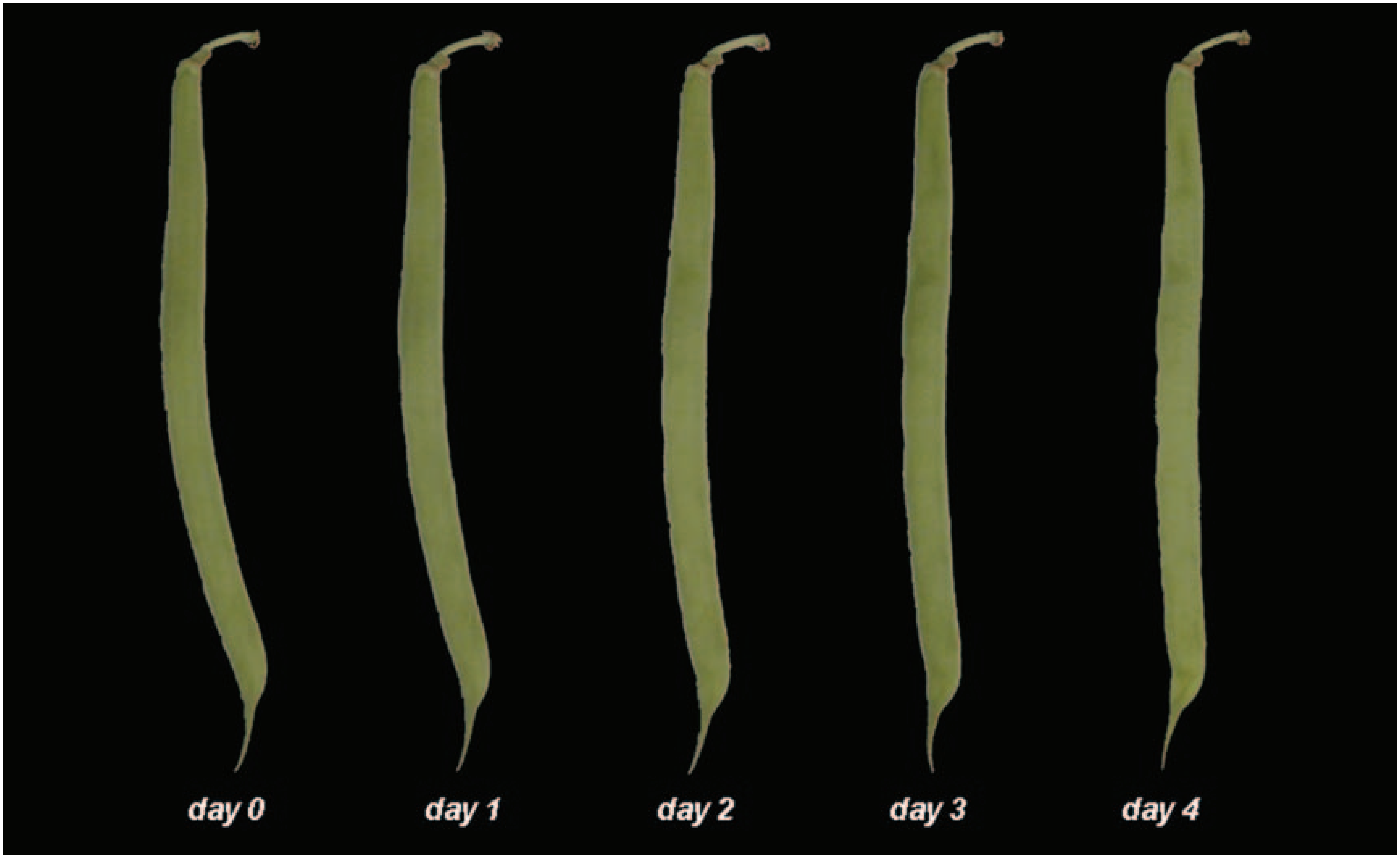
day 0
day 1
day 2
day 3
day 4

Figure 6.14. Appearance of 'Opus' snap beans stored for 4 days at 10°C. Snap beans maintain acceptable visual quality during 3 days. After 3 days shriveling is evident at the tip of the pod.

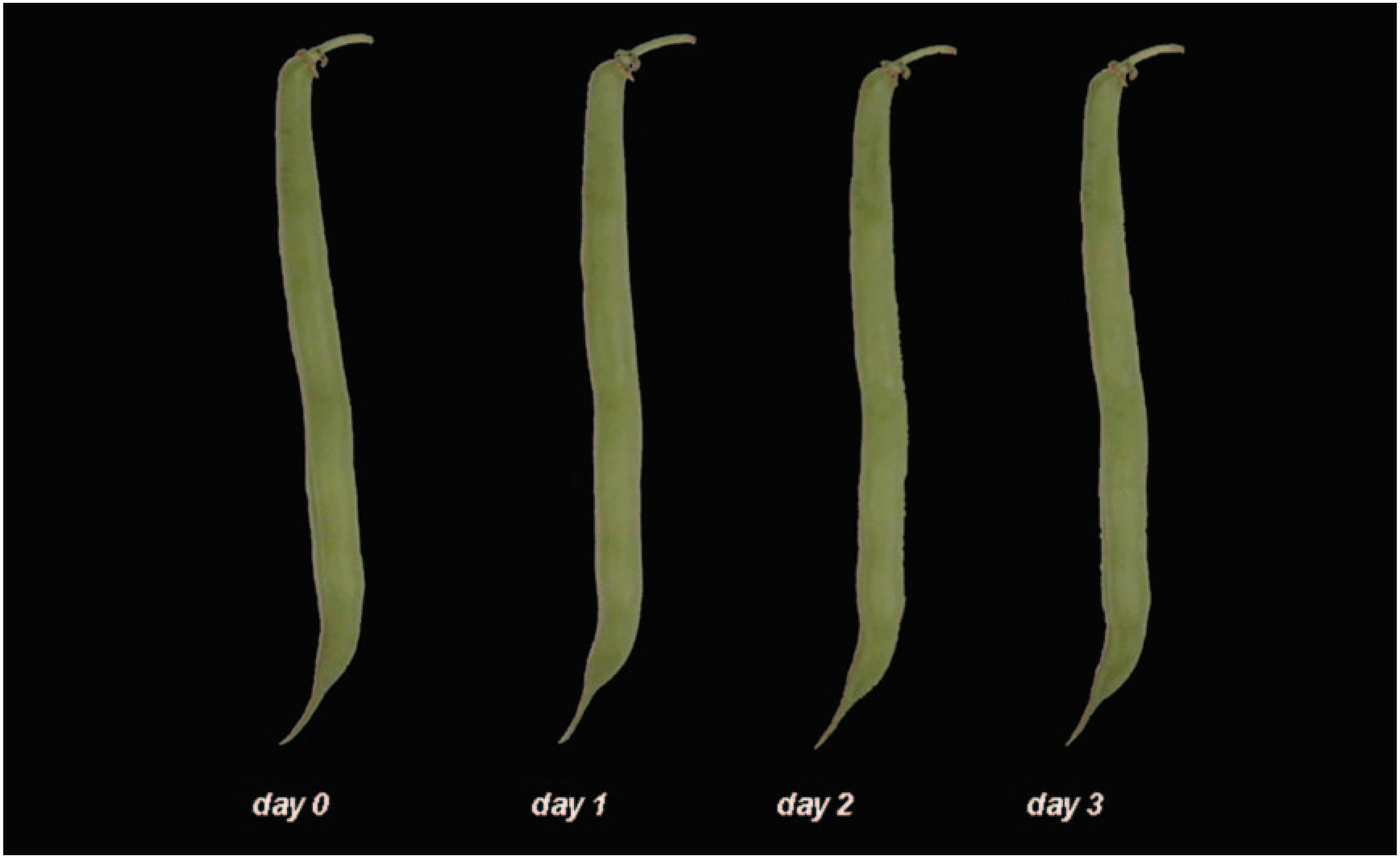

Figure 6.15. Appearance of 'Opus' snap beans stored for 3 days at 15°C. Snap beans maintain acceptable visual quality during 2 days. After 2 days shriveling is evident at the tip of the pod.

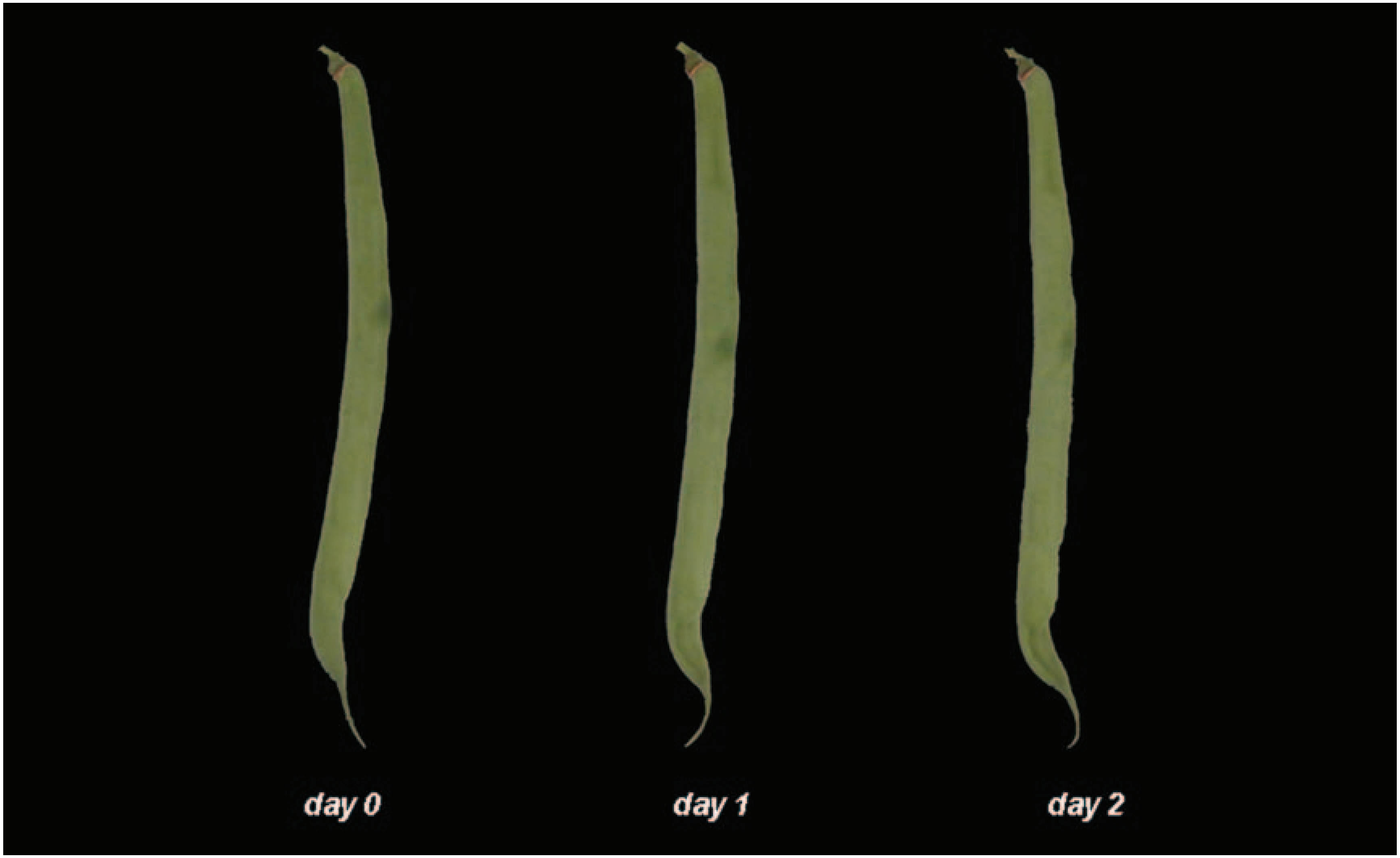

Figure 6.16. Appearance of ‘Opus’ snap beans stored for 2 days at 20°C. After 1 day the pod shows severe shriveling of the tips.

CABBAGE

Scientific Name: *Brassica oleraceae* L. var. *capitata*
Family: Brassicaceae

Quality Characteristics

Cabbage has been cultivated for many years and was highly valued by the Greeks and Romans, who may have introduced this vegetable into Europe. Cabbage is now one of the most cultivated vegetables in temperate climates. Although the majority of cabbage cultivars are of the green (white) type, there are cultivars that have red or purple leaves and others, such as the Savoy types, that have wrinkled leaves. The most important types of cultivated cabbage are the green (i.e., domestic, Danish, conical, or pointed-head types), red, and Savoy types. The green cabbage is the most important class and is grown mostly as an early to mid-season crop. This group includes cultivars with round or slightly flattened heads that are characterized by tender and brittle leaves. The leaves of the domestic type are a little crinkled or curled and do not overlap as much as the ones in the Danish type, forming a less compact head. The Danish types are usually late maturing and have a solid, round to oval-shaped head, and the leaves are usually smooth and closely compact. The red types produce compact heads with reddish or purplish tender and flat leaves, whereas the Savoy types have very crinkled and thick leaves (Pritchard and Becker 1989).

Cabbage heads are generally compact and consist of many thick, overlapping leaves that are oval to circular in shape and surround the merismatic growing region (Pritchard and Becker 1989). Good quality cabbage should have firm or hard heads that are heavy for their size. The outer leaves should be of a bright green color, crisp and fresh, and free from blemishes. The leaves are considered fresh if they squeak when rubbed together (Boyette et al. 1999; Pritchard and Becker 1989), and the presence of a waxy bloom on the leaves is also considered a good indication of freshness (Prange 2004). The major signs of loss of quality are yellowing of the outer leaves, core elongation, internal yellowing in the apex region, leaf abscission, and sometimes rootlet development at the core-end (Pritchard and Becker 1989; Cantwell and Suslow 2007c). Separation of the petioles of the leaves from the central stem at the base of the head indicates senescence and loss of quality (Pritchard and Becker 1989). The bright dark green outer leaves of a cabbage are usually trimmed before sale, exposing the inner leaves that are usually a pale green color. For that reason, most of the cabbages available at the market have a light yellowish-green color. Yellowish-green leaves on green cabbage cultivars, however, suggest extensive trimming of the outer leaves (Prange 2004).

The main constituents of green cabbage are carbohydrates, comprising nearly 90% of the dry weight, where approximately one-third is dietary fiber and two-thirds is low molecular weight carbohydrates (Rani and Kawatra 1994; Wennberg et al. 2006). Freshly harvested cabbage contains on average 90.6–92.5% water, 1.2% protein, 0.12–0.18% lipids, 5.4% carbohydrates, and 1.6–6.2% fiber (USDA 2006; Wennberg et al. 2006). Total sugar content varies depending on the cabbage cultivar from about 3–9%. Glucose (1.40–2.06%) is the most important sugar, followed by fructose (1.06–1.74%) and sucrose (0.02–0.05%) (Pritchard and Becker 1989; USDA 2006; Wennberg et al. 2006). The predominant fatty acids in the total lipid analyses of cabbage are linolenic, linoleic, oleic, palmitic, and stearic acids (Peng 1973, 1982; Wheeldon 1960).

Cabbage has long been recognized as an important source of ascorbic acid (vitamin C), containing from about 5.7–83 mg/10 g fresh weight (Bushway et al. 1989; Kurilich et al. 1999; Marlett and Vollendorf 1993; Noble 1967; Podsedek 2007; Proteggente et al. 2002; Singh et al. 2006; USDA 2006; Vanderslice et al. 1990). The pointed-head cultivars usually contain more ascorbic acid than other cabbage cultivars, with the early maturing types generally having higher levels than the late mature types. The highest levels of ascorbic acid are found in the outer green leaves and in the edible portion of the core. Cabbage is also very rich in S-methylmethionine (up to 20.7 mg/100 g fresh weight), a derivative of methionine, also known as vitamin U or the anti-ulcer factor. Vitamin U is enzymatically or non-enzymatically broken down into homoserine and dimethylsulfide. Volatile dimethylsulfide is one of the quality components of cabbage (Bezzubov and Gessler 1992; Howard and Russell 1997; Takigawa and Ishii 2000).

Vitamin A content is relatively low in cabbage (126 IU/100 g fresh weight), with the highest levels found in the outer green leaves due to the higher carotenoid concentration, while mature heads contain less vitamin A than immature heads (Pritchard and Becker 1989; USDA 2006).

The β-carotene content of different cabbage cultivars ranged from 0.009 to 0.41 mg/100 g fresh weight, while lutein content ranged from 0.021 to 0.45 mg/100 g fresh weight (Podsedek 2007; Singh et al. 2006). Vitamin E (DL-α-tocopherol) in different cabbage cultivars ranged from 0.030 to 0.509 mg/100 g fresh weight (Kurilich et al. 1999; Singh et al. 2006).

Cabbage is also rich in total phenolic compounds (12.58–203 mg/100 g fresh weight), particularly in hydroxycinnamic (37.9–50.4 mg/100 g fresh weight) and kaempferol (12.8–17.2 mg/100 g fresh weight) conjugates, which confer a good antioxidant capacity to cabbage (Ferreres et al. 2006; Heimler et al. 2006; Hertog et al. 1992; Melo et al. 2006; Podsedek 2007; Proteggente et al. 2002; Singh et al. 2006). There is, however, a large variation in the antioxidant phytochemical contents among cabbage cultivars. Higher vitamin C, vitamin E, and phenolic contents were found in red cabbage, higher β-carotene was found in Savoy cabbage, while higher lutein content was found in white cabbage (Singh et al. 2006). Phenolic compounds together with vitamin C constitute the major antioxidants in cabbage, due to their high content and high antioxidant activity, while carotenoids and vitamin E are only responsible for 20% of the total antioxidant activity in cabbage (Podsedek 2007).

Other characteristic components of cabbage are glucosinolates, which are sulphur-containing glycosides. The sharp, biting, and pungent taste of cabbage has been attributed to the breakdown products of glucosinolates, and these compounds are believed to have a protective effect against cancer (Verhoeven et al. 1977). Green cabbage cultivars may contain between 1,280 and 1,457 μg of glucosinolates per 100 g dry weight (Guffy and Hicks 1984; Kushad et al. 1999; Song and Thornalley 2007; Wennberg et al. 2006). Among all the desirable flavor compounds (i.e., sulfur, saturated aldehydes, saturated alcohols, unsaturated aldehydes, unsaturated alcohols, ketones, isothiocyanates, and nitriles) identified in cabbage cultivars, sulfur compounds and saturated alcohols followed by saturated aldehydes were most abundant (MacLeod and Nussbaum 1977).

Optimum Postharvest Handling Conditions

Cabbage should be pre-cooled as soon as possible after harvest to reduce wilting. Hydro-cooling before storage or forced-air cooling can be used to remove field heat (Boyette et al. 1999). A temperature of 0°C with a 98–100% relative humidity is recommended for long-term storage of cabbage in order to reduce moisture loss and yellowing (Parsons et al. 1960; Pritchard and Becker 1989; Prange 2004). The maximum storage life and retention of cabbage quality varies greatly depending on the cabbage type, cultivar, and storage conditions. Early cabbage is generally stored for short periods of 3–6 weeks, while late cultivars can maintain their quality for 6–7 months (Cantwell and Suslow 2007c; Pritchard and Becker 1989). Storage under light may reduce physiological disorders such as leaf yellowing and weight loss (Perrin 1982; Prange and Lidster 1991), while exposure to ethylene may reduce cabbage quality due to enhanced yellowing and accelerated senescence (Prange 2004).

Temperature Effects on Quality

Bacterial soft rot, yellowing, and discoloration were reported to be the major causes of cabbage deterioration in shipments arriving to the New York market from different locations worldwide. Bacterial soft rot affected 60% of the cabbage shipment, followed by yellowing and black discoloration, which affected on average 16 and 14% of the shipments, respectively (Ceponis et al. 1987). Core elongation was also observed in stored cabbage. After 15 weeks of storage at 0–1°C, core elongation started to be evident, and after 6 months stalks emerged from most of the cabbage heads (Guffy and Hicks 1984). Loss of green color was also rapid when cabbage was stored at temperatures >0°C (Parsons et al. 1960). Color of cabbage stored at 0°C shifted from a dark dull green toward a light (higher L*), brighter (higher saturation), and more yellow hue during storage. Chlorophyll content and color intensity also declined as trim loss increased, due to removal of greener outer leaves (Prange and Lidster 1991).

Weight loss of cabbage increases during the postharvest period, as storage time and temperature increase (Sundstrom and Story 1984). For example, weight loss in cabbage stored at 0°C increased from 5.6% after 3 months to 9.5% after 6 months (Prange and Lidster 1991). After 6 months, weight loss of cabbage stored at 0–1°C attained 3.9–5.7% of the initial weight, depending on the cultivar and season of harvest (Nilsson 1993). Weight loss of Chinese cabbage also increased during storage, attaining 2.1% after 9 weeks of storage at 2°C (Porter et al. 2004). Cabbage stored in a domestic refrigerator with temperatures ranging from 4 to 8°C lost about 3% of the initial weight after 7 days, while maximum weight loss in cabbage stored at ambient temperature (12–22°C) was 9.6% of the initial weight. After 7 days, cabbage stored at ambient temperature was visibly decayed and dry (Song and Thornalley 2007). Weight loss of cabbage increased with the length of storage period and ranged from 5.0% of the initial weight after 3 or 4 weeks at 0°C to 13.7% after 7–8 weeks at 7°C. This weight loss corresponded to a moderate to severe wilting, respectively (Parsons et al. 1960). When weight loss exceeded 5% of the initial weight loss, cabbage showed visible wilting (Parsons 1959), while maximum weight loss before cabbage became unacceptable for sale ranged from 7 to 10%, depending on the cultivar (Robinson et al. 1975).

Weight reduction during storage of cabbage is not only attributed to loss of moisture due to transpiration but also to trimming of damaged external leaves. Regular trimming of senescing leaves from cabbage heads during storage results not only in loss of the typical bright green cabbage color but also in loss of profit as it produces a lower marketable head weight and significantly higher labor cost. However, trimming of cabbage during storage seems to be inevitable and losses of up to 20% during long-term storage can be expected due to moisture loss, leaf discoloration, and decay (Pritchard and Becker 1989). Trimming losses increased with storage time and temperature, and after 7–8 weeks overall losses due to decayed, broken, or discolored leaves that had to be removed ranged from 8.1 to 13.4% in cabbage stored at 0°C, from 8.2 to 18.6% in cabbage stored at 4°C, and from 13.8 to 31.6% in cabbage stored at 7°C (Parsons 1959; Parsons et al. 1960). In cabbage stored at 0°C, trim losses ranged from 15.8 to 19.5% after 3 months, and from 22.3 to 22.6% after 6 months, depending on the cultivar (Prange and Lidster 1991). Likewise, in Chinese cabbage, trimming losses increased from 16.2% to about 25% after 9 weeks at 0°C (Klieber et al. 2002), while trimming losses in cabbage stored at 2°C attained a maximum of 42.7% after 9 weeks (Porter et al. 2004).

High-humidity storage or plastic film wrapping have been successfully used to protect cabbage from loss of moisture during prolonged storage. The use of perforated or nonperforated polyethylene crate liners reduced the weight loss of stored cabbage to less than 1% after 7–8 weeks at 0 or 7°C. Cabbage green color was retained for longer periods, and losses due to discoloration, wilting, and decay were usually less in polyethylene-lined than in unlined crates (Parsons et al. 1960). Storage of cabbage at 98–100% relative humidity reduced decay, moisture loss, and color loss, compared to storage at 90–95% relative humidity, regardless of the temperature. After 30 days, weight loss of cabbage stored at 90–95% relative humidity attained 1.6, 2.2, and 2.6% in cabbage stored at 0–1°C, 3.5–4.5°C, and 7–8°C, respectively. On the other hand, weight loss of cabbage stored at 98–100% relative humidity attained 0.5, 0.7, and 1.4% after 30 days under the same temperature conditions. Consequently, cabbage stored at higher humidity remained firm and crisp and retained its green color longer. Storage life of cabbage stored at 3.5–4.5°C was limited to 4–5 months, while storage life of cabbage stored at 7–8°C was reduced to 2–3 months due to internal growth and rooting. At 0–1°C there was little rooting and internal growth after 7 months (van den Berg and Lentz 1973).

Compositional changes were also observed during prolonged storage of cabbage. For example, fructose and glucose contents decreased during storage of cabbage for 6 months at 0–1°C, while sucrose and soluble solids content decreased from the time of harvest until 4 months of storage, increasing afterward to a level comparable to that at the time of harvest (Nilsson 1993).

Ascorbic acid content may be reduced from 51 to 42 mg/100 g fresh weight during storage of cabbage (USDA 2006). One day after harvest ascorbic acid content of cabbage was reduced by approximately 22% (Vanderslice et al. 1990). However, others have shown ascorbic acid retention of 95% in green cabbage stored for 3 weeks at 2°C and 95–100% relative humidity, while sulfur content increased from an initial value of 66.04 mg/100 g to 70.40 mg/100 g fresh weight under the same storage conditions. The same authors concluded that sulfur-containing compounds found in cabbage might be involved in ascorbic acid retention (Albrecht et al. 1990).

Vitamin U (S-methylmethionine) content of the inner and middle layer leaves increased in cabbage stored for 92 days at 4°C, while it decreased in the outer leaves (Takigawa and Ishii 2000). Glucosinolate content of five different cabbage cultivars stored for 6 months at 0–1°C tended to increase during storage (Guffy and Hicks 1984). When stored at 12–22°C for 7 days there was no significant decrease in the glucosinolate content of green cabbage, yet when stored in a domestic refrigerator at 4–8°C, the total glucosinolate content of green cabbage decreased from an initial value of 10.3 μmol/100 g to 8.9 μmol/100 g after 7 days (Song and Thornalley 2007).

Time and Temperature Effects on the Visual Quality of 'Farao' Cabbage

'Farao' early green cabbages shown in Figures 6.17–6.22 were harvested at the mature stage, with firm and compact heads, from a commercial operation in the Orleans Island, Quebec, Canada, during the summer season (i.e., July). Promptly after harvest, fresh cabbages were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Major changes in the visual quality attributes of 'Farao' green cabbage during storage at different temperatures include changes in color, wilting and dryness of the leaves, loss of head density, leaf separation, and slight core elongation. Green cabbage stored at 0°C maintains acceptable visual quality during 18 days. After 18 days, the outer leaves become less bright green, wilted, and less turgid than at harvest, while few brownish lines develop on the leaves. Cabbage head loses compactness, the leaves separate from each other, and after 20 days slight core elongation is perceptible (Figure 6.17). At this point if cabbage was marketed the outer leaves would have to be trimmed, exposing less green leaves.

'Farao' cabbage stored at 5°C maintains acceptable visual quality during 12–18 days. However, after 18 days the outer leaves appear less turgid and slightly wilted compared to harvest, while they lose their bright green color. After 22 days, the outer leaves become yellowish, and simultaneously the cabbage head loses its compactness, the internal leaves separate from each other, and core elongation is evident (Figure 6.18).

Deterioration in the visual quality of 'Farao' green cabbage stored at 10°C occurs much faster than at lower temperatures, and after only 6 days the external leaves become wilted and yellowish-green, with incipient brown discoloration (Figure 6.19). Appearance of the external leaves continues to deteriorate, and after 24 days the external leaves develop a brownish-green discoloration with some yellowish patches, while the internal leaves appear limp and loose. The cabbage head at this point is soft and spongy on touch.

Yellowing of the external leaves develops very quickly in cabbage stored at 15°C, and after 6 days yellowing is already perceptible in some of the leaves (Figure 6.20). Wilting of the external leaves is also very fast, and after 24 days the leaves appear completely wilted and yellowish, while the internal leaves lose their compactness and appear loose and limp. Core elongation is also evident, as well as re-rooting (Figure 6.21). The cabbage head is very soft and cedes easily when squeezed.

During storage at 20°C, color of ‘Farao’ green cabbage changes very quickly, from a bright green to a yellowish-green (Figure 6.22). After 18 days, the edges of the external leaves turn yellow, and after 24 days become brownish-yellow. Simultaneously, the leaves become very flaccid and the cabbage head loses compactness due to loosening of the internal leaves. At this point, the cabbage head feels extremely soft when squeezed.

Overall, ‘Farao’ green cabbage maintains better quality for longer periods of time when stored at 0°C (18 days). As storage temperature increases cabbage visual quality attributes deteriorate very quickly. Therefore, the appearance of cabbage stored at temperatures between 5 and 20°C becomes objectionable after 12 to less than 6 days, respectively.

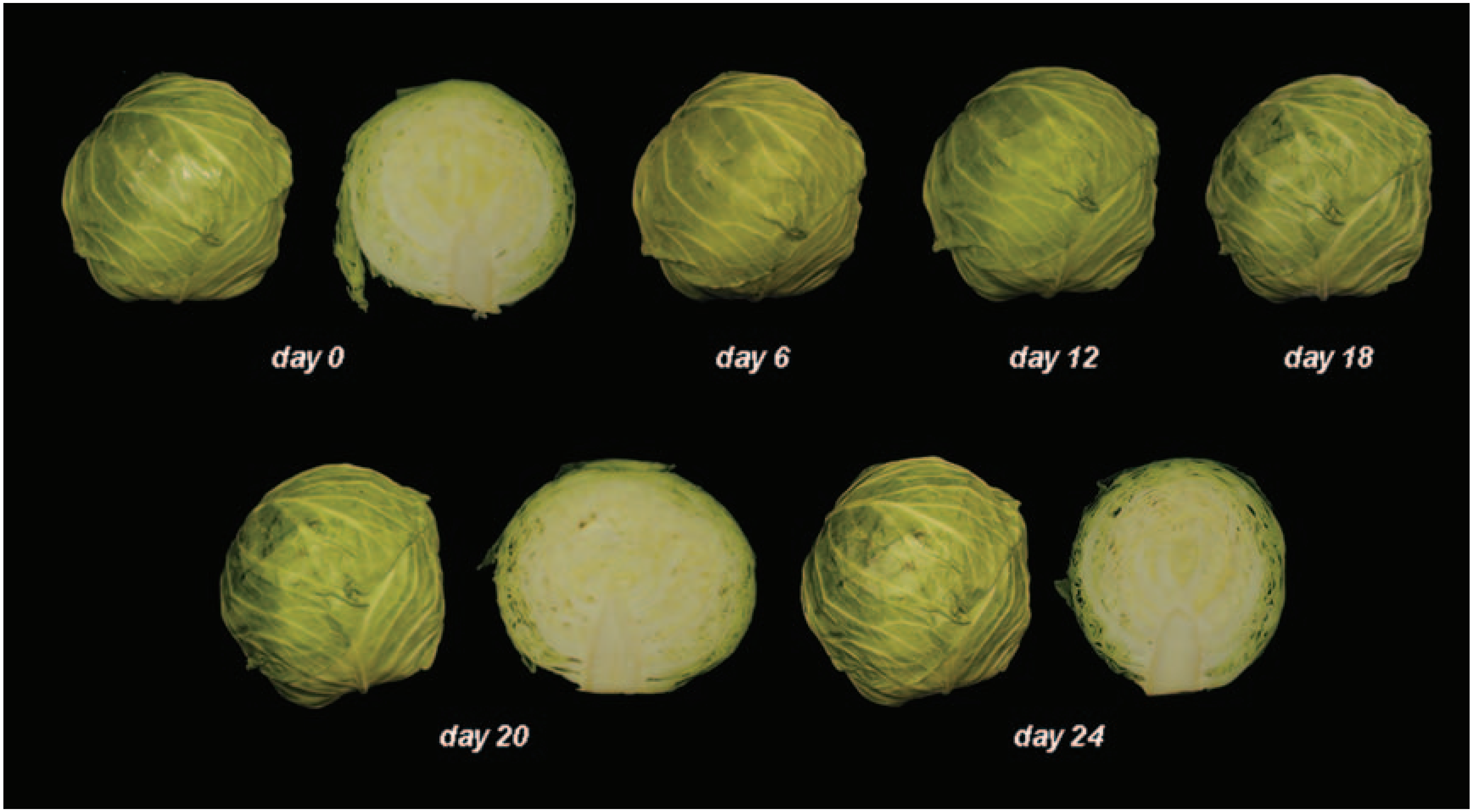
day 0
day 6
day 12
day 18
day 20
day 24

Figure 6.17. Appearance of 'Farao' cabbage stored for 24 days at 0°C. After 18 days the external leaves develop some browning and appear wilted, while the internal leaves appear less compact than at harvest.

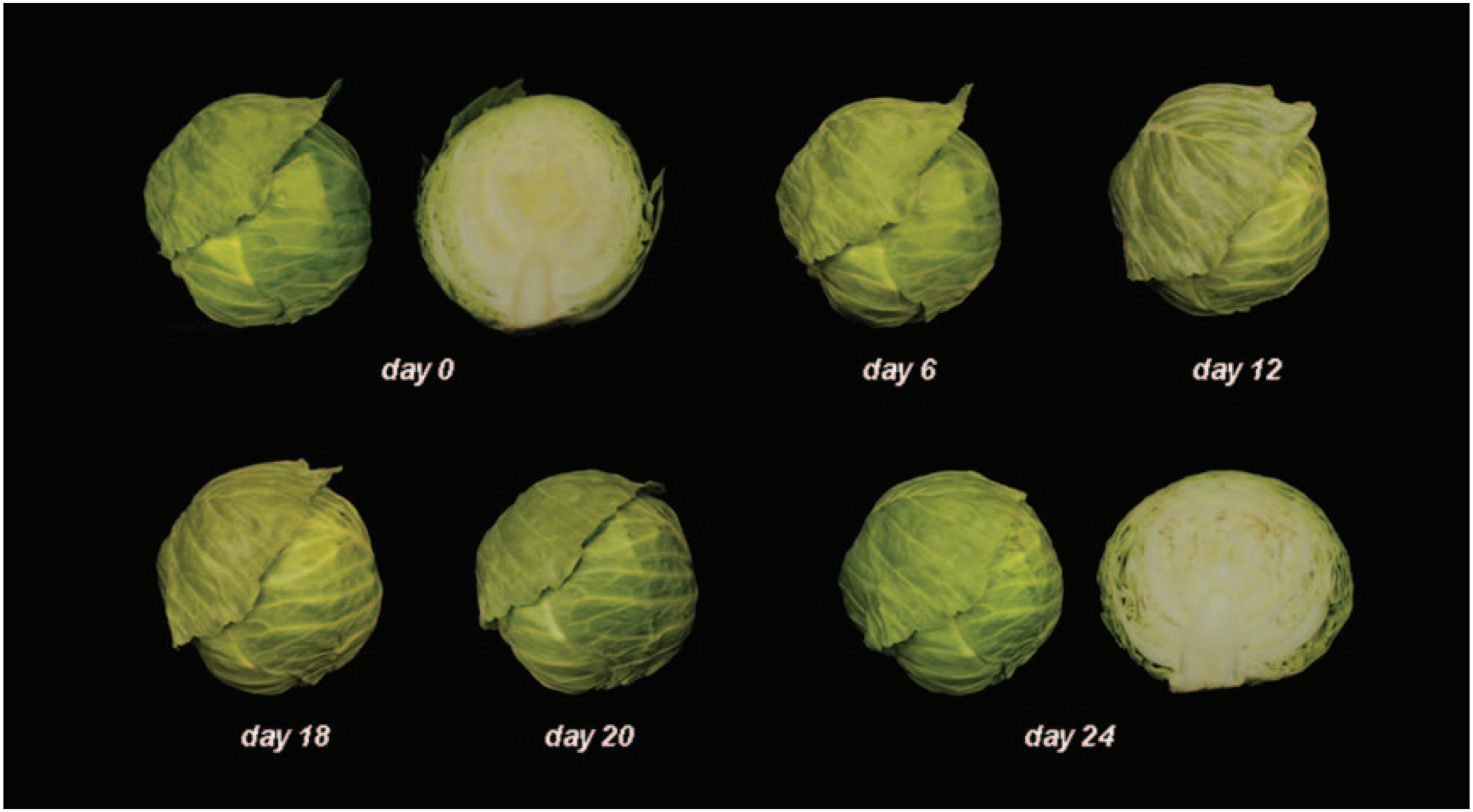
day 0
day 6
day 12
day 18
day 20
day 24

Figure 6.18. Appearance of ‘Farao’ cabbage stored for 24 days at 5°C. After 18 days the external leaves appear less turgid and more yellowish-green than at harvest, while the internal leaves appear less compact.

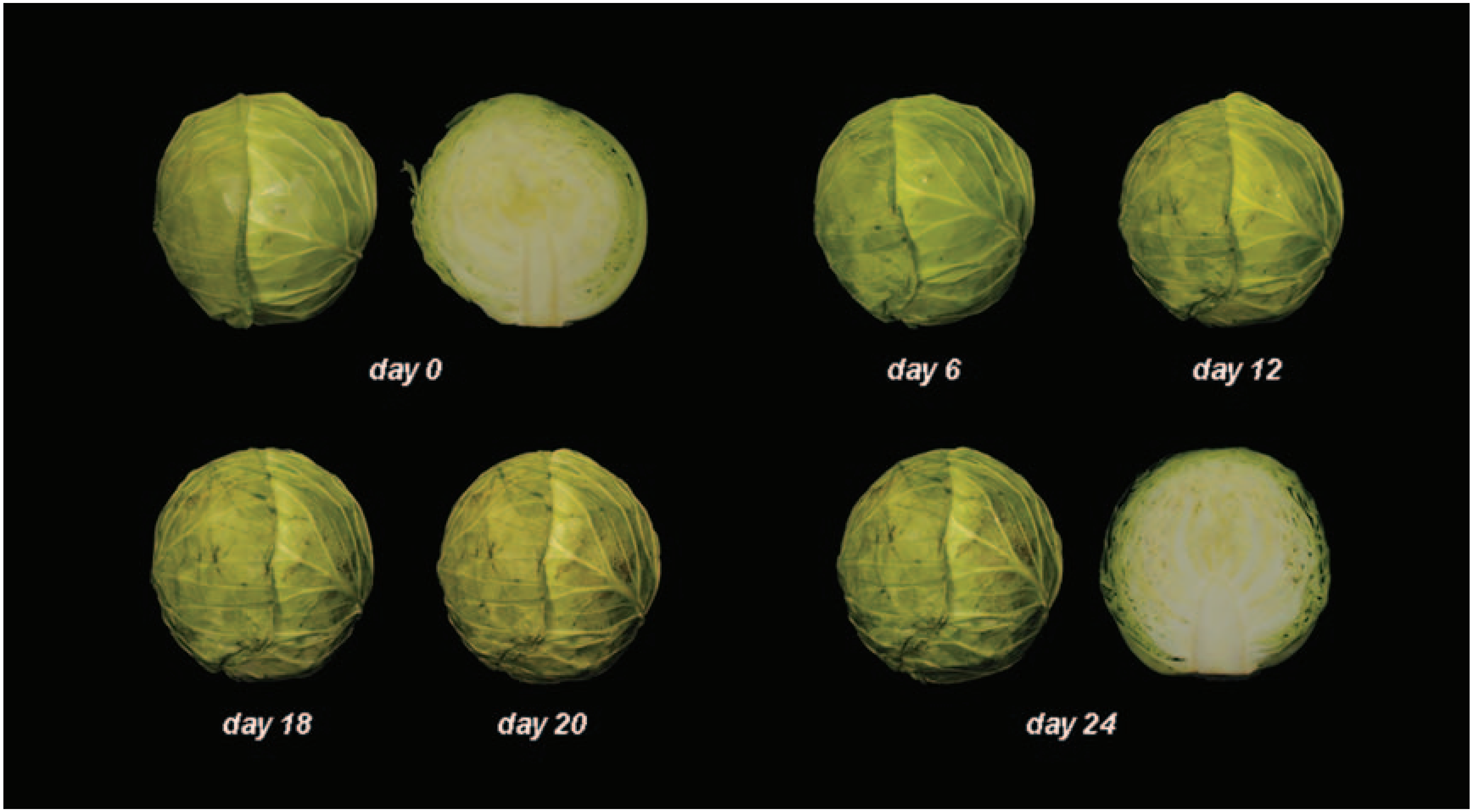
day 0
day 6
day 12
day 18
day 20
day 24

Figure 6.19. Appearance of 'Farao' cabbage stored for 24 days at 10°C. After 6 days the appearance of the external leaves deteriorates, becoming dry and brownish-green. After 24 days the internal leaves appear limp and loose.

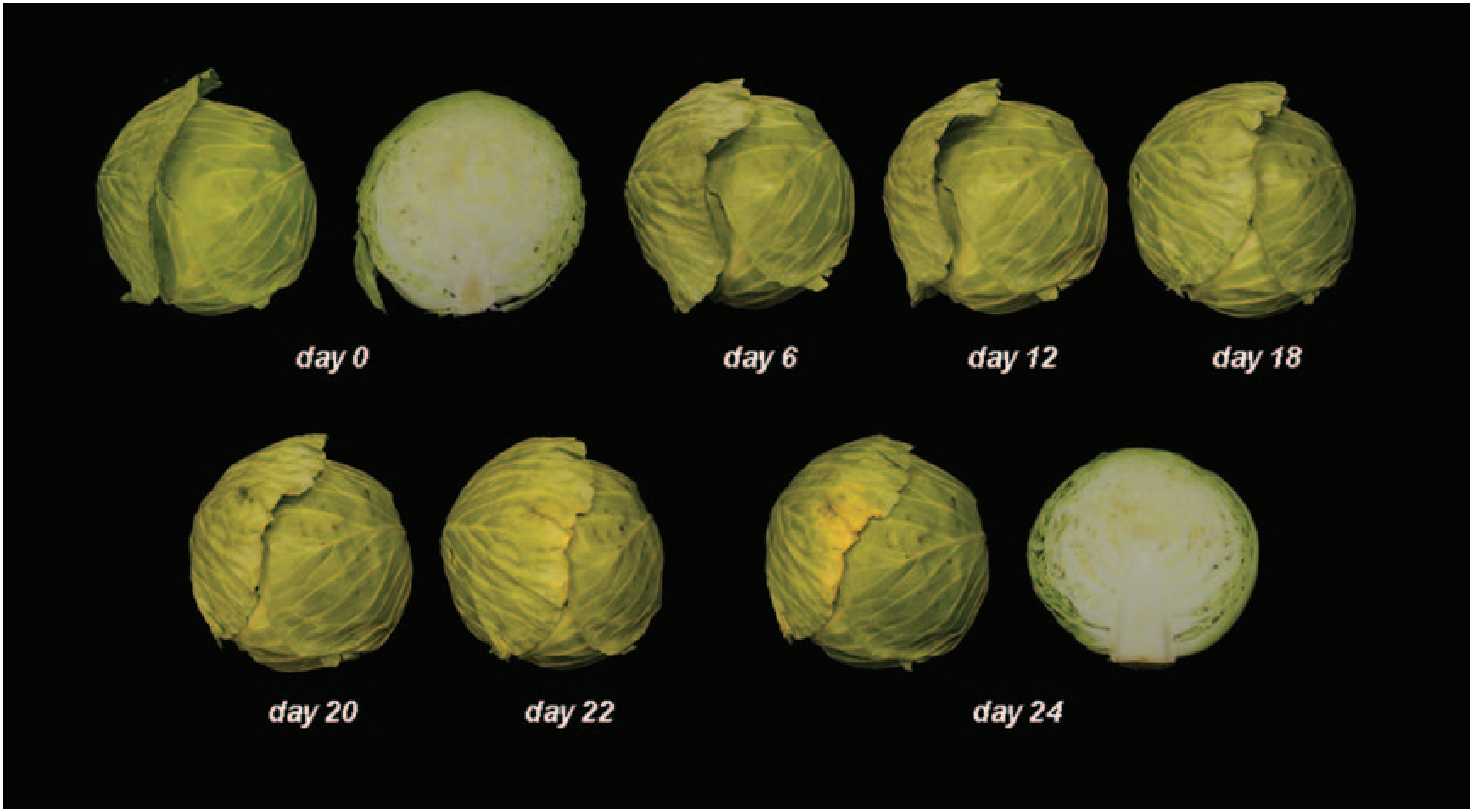
day 0
day 6
day 12
day 18
day 20
day 22
day 24

Figure 6.20. Appearance of 'Farao' cabbage stored for 24 days at 15°C. After 24 days the external leaves develop severe yellowing, while the internal leaves appear limp and loose.

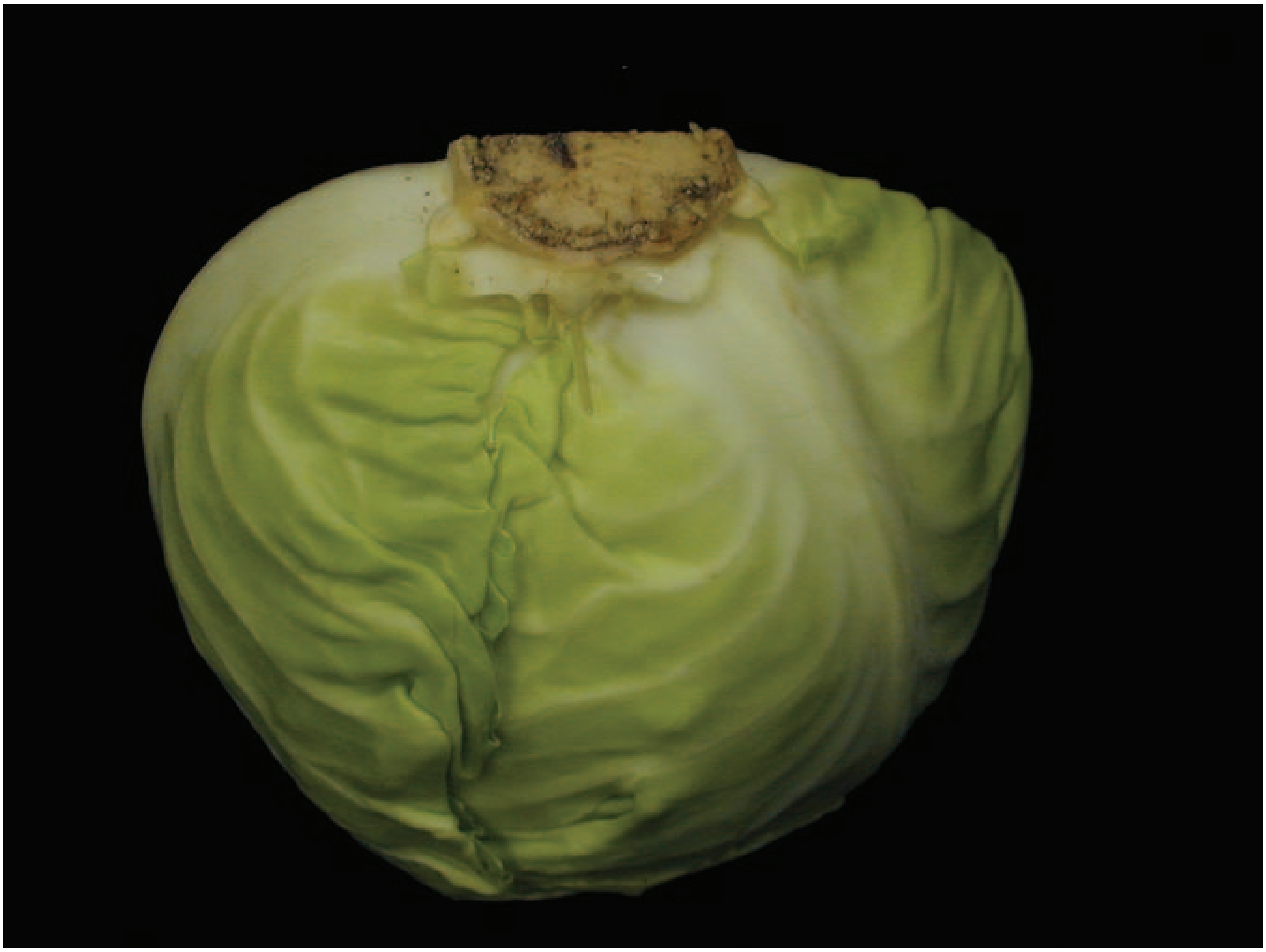

Figure 6.21. Rerooting in ‘Farao’ cabbage after 24 days at 15°C.

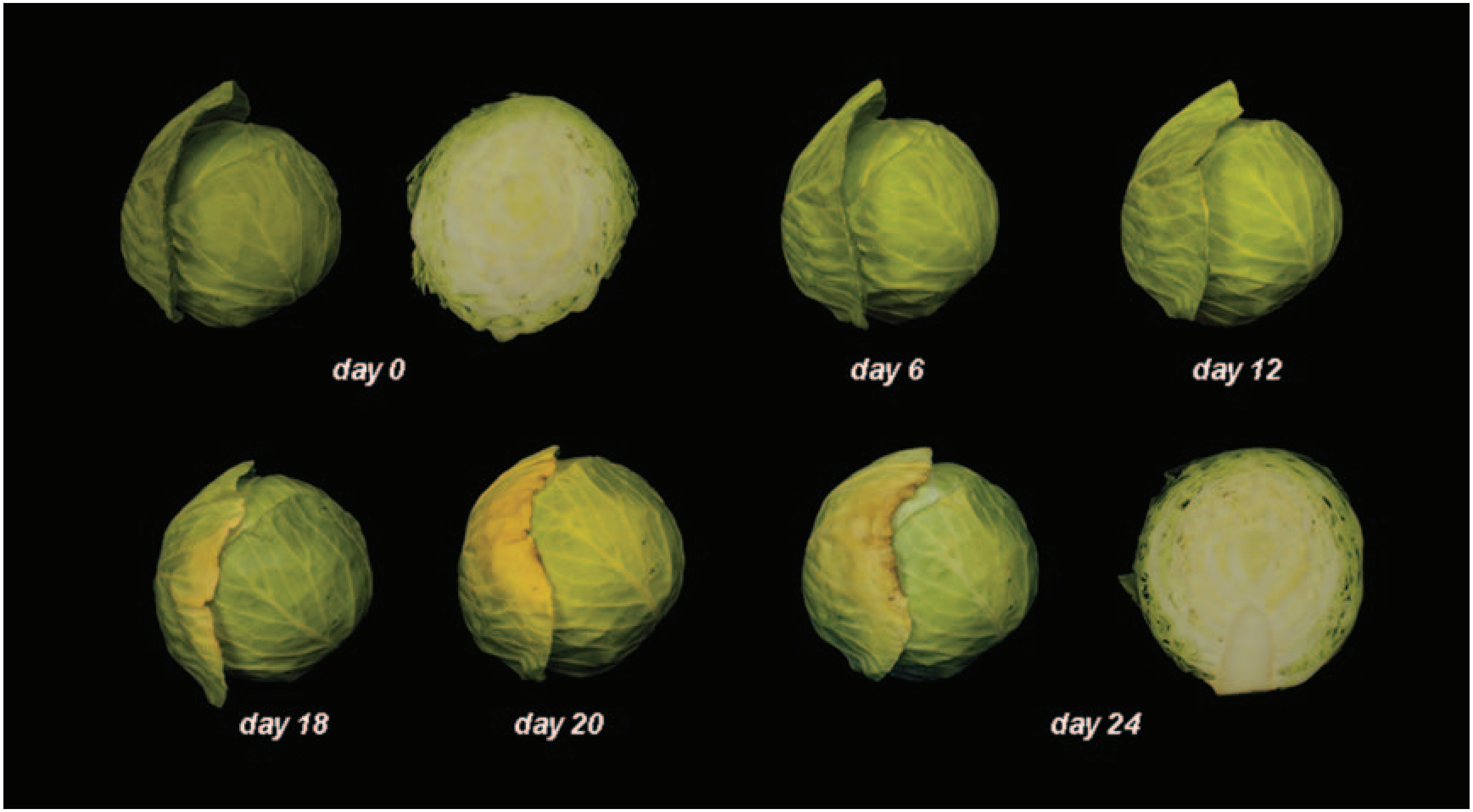
day 0
day 6
day 12
day 18
day 20
day 24

Figure 6.22. Appearance of 'Farao' cabbage stored for 22 days at 20°C. After 18 days the external leaves turn yellow, and after 24 days the internal leaves appear limp and loose.

CAULIFLOWER

Scientific Name: *Brassica oleracea* L. var. *botrytis* L.
Family: Brassicaceae

Quality Characteristics

Cauliflower is a derivative from the wild cabbage and has been cultivated, like other *Brassica* varieties, for many years. Cauliflower is usually grown during cool seasons, and as soon as the white curd starts to develop the leaves are tied to wrap the curd in order to protect it from direct exposure to sunlight, which may cause undesirable yellowish or green discoloration. Best quality cauliflower should have a snow-white color, with compact, firm, and relatively smooth curds, surrounded by well-trimmed turgid green leaves (Andersen 2007; Forney and Toivonen 2004b; Ryall and Lipton 1979). Mature cauliflower curds are at least 15 cm in diameter (Suslow and Cantwell 2007). Slightly yellowish curds are not necessarily a sign of inadequate postharvest handling but are rather a consequence of incomplete shading and exposure of the curd to sunlight during maturation on the plant, resulting in increased chlorophyll synthesis (Anonymous 2004b; Ryall and Lipton 1979). Although slightly yellow curds are not as acceptable in terms of appearance, they are still good for consumption. On the other hand, dark cream to yellow cauliflower curds tend to be excessively strong flavored. Dark spotted, "ricy" (i.e., loose or protruding floral parts), or yellowish curds are signs of inadequate postharvest handling and senescence (Forney and Toivonen 2004b; Ryall and Lipton 1979; Suslow and Cantwell 2007).

In general, consumers prefer cauliflower that is white, sweet, crisp, juicy, and with characteristic cauliflower flavor. More intense bitter, pungent, green, or grassy flavors tend to reduce cauliflower acceptability (Brückner et al. 2005; Fjeldsenden et al. 1981; Schonhof et al. 2004). Although sugar content does not seem to significantly influence the sweetness of cauliflower, glucosinolate content affects sweetness as well as bitter and pungent flavor. That is, the higher the glucosinolate content the more bitter and pungent the cauliflower tastes. Cauliflower cultivars with a glucosinolate content of <30–35 mg/100 g fresh weight were in general preferred due to their low bitter and pungent flavor (Brückner et al. 2005; Schonhof et al. 2004).

Even though the white type is the most popular cauliflower cultivated, colored cultivars are increasing in popularity due to their attractive color, better taste (i.e., more sweet and less intense flavor), and higher nutritional values (Cebula et al. 2006; Gajewski and Radzanowska 2003). For example, green (43.8 g/100 g fresh weight) and romanesco (38.6 mg/100 g fresh weight) cauliflowers contained on average higher ascorbic acid content than white cauliflower (30.4 mg/100 g fresh weight). While white cauliflower contains negligible amounts of carotenoids (Kurilich et al. 1999), green and romanesco cauliflower carotenoid content was on average 0.9 and 1.1 mg of carotenoids/100 g fresh weight, respectively (Cebula et al. 2006; USDA 2006). In general, white cauliflower contains on average 87–92% water, 2% protein, 0.1% lipids, 5.3% carbohydrates, 2.5% fiber, 1.4–2.6% total sugars, and about 15.0–82.6 mg ascorbic acid/100 g fresh weight (Albrecht et al. 1990, 1991; Bushway et al. 1989; Cebula et al. 2006; Kurilich et al. 1999; Lo Scalzo et al. 2007; Noble 1967; Podsedek 2007; Proteggente et al. 2002; Schonhof et al. 2004; Rani and Kawatra 1994; USDA 2006; Vanderslice et al. 1990). Green cauliflower contains on average 89.9–91.4% water, 3.0% protein, 0.3% lipids, 6.1% carbohydrates, 3.2% fiber, 2.2–3.03% total sugars, 43.8–88.1 mg ascorbic acid, and 137 μg of carotene, lutein, and zeaxanthin/100 g fresh weight (Cebula et al. 2006; USDA 2006).

Fructose (0.76–1.29 g/100 g fresh weight) and glucose (0.6–1.02 g/100 g fresh weight) were the main sugars identified in cauliflower cultivars, followed by sucrose (0.06–0.35 g/100 g fresh weight). Unlike in white cauliflower cultivars, sucrose (1.09 g/100 g fresh weight) was the main sugar identified in green cauliflower (Schonhof et al. 2004). Cauliflower also contains glucosinolates (13.5–77 μmol/100 g fresh weight) and sulfur (63.51 mg/100 g fresh weight) compounds in generous amounts. Although some of these compounds confer a bitter and pungent taste, they have been associated with beneficial anticarcinogenic properties (Albrecht et al. 1990; Branca et al. 2002; Kushad et al. 1999; Schonhof et al. 2004; Song and Thornalley 2007; Verhoeven et al. 1977). Cauliflower contains phenolic compounds (4,041.4–6,492.6 mg/kg dry weight), from which 1,690 mg/kg dry weight are flavonoids and 560 mg/kg dry weight are tannins (Heimler et al. 2006; Lo Scalzo et al. 2007). The main unsaturated fatty acid found in cauliflower was linolenic (60–120 mg/g dry weight), while the main saturated fatty acid was palmitic with a content ranging from 30 to 60 mg/g dry weight. Polyphenols and vitamin C showed a good correlation with antioxidant capacity of cauliflower (Lo Scalzo et al. 2007; Melo et al. 2006), whereas the lipid-soluble antioxidants (linolenic acid, carotenoids, and vitamin E) were responsible for up to 20% of the total antioxidant activity (Podsedek 2007).

Optimum Postharvest Handling Conditions

Following harvest, cauliflower should be promptly precooled before storage. Hydro-cooling or vacuum-cooling have been typically used to pre-cool cauliflower, but forced-air cooling can also be used (Forney and Toivonen 2004b; Ryall and Lipton 1979). When vacuum-cooling is used cauliflower should be wetted prior to cooling to avoid excessive loss of moisture (Stewart and Barger 1961). After precooling, cauliflower should be stored at 0°C with a relative humidity of 95–98%. Increasing the relative humidity of the surrounding environment to 100% will further reduce weight loss and wilted appearance of cauliflower (van den Berg and Lentz 1973). Expected postharvest life under these conditions is usually 2 weeks (Ryall and Lipton 1979). However, wilting, browning, yellowing of the leaves, and decay may occur after prolonged storage at higher recommended storage temperatures (Forney and Toivonen 2004b; Suslow and Cantwell 2007). In general, when stored at 0°C, postharvest life of good quality cauliflower is about 21–28 days, 3°C is about 14 days, while at 5°C postharvest life is reduced to 7–10 days. When stored at 10°C, quality of cauliflower is retained during about 5 days and at 15°C during only 3 days (Herregods 1964; Koike et al. 1997).

In order to reduce wilting, cauliflower is usually wrapped in plastic film before marketing. The film should, however, be perforated with four- to six-millimeter perforations to prevent off-colors and off-odors as a result of exposure to low oxygen levels (Anonymous 2004b; Forney and Toivonen 2004b; Sanders 2001). Due to the extreme susceptibility of the white cauliflower curd to develop browning and decay on bruised areas, cauliflower should never be allowed to roll or have the white curd contact flat surfaces (Koike et al. 1997; Suslow and Cantwell 2007). Exposure to exogenous ethylene may reduce cauliflower quality due to discoloration of the curd, accelerated yellowing, and detachment of wrapper leaf stalks (Brackmann et al. 2005; Suslow and Cantwell 2007).

Temperature Effects on Quality

Cauliflower is a highly perishable vegetable, and its sensorial and compositional quality deteriorates very quickly if handled improperly. Brown discoloration of the curd (81.6%) and bacterial soft rot (57.5%) were the main causes of cauliflower deterioration in shipments arriving to the New York market (Ceponis et al. 1987). Bacterial soft rot and curd spotting, which were associated with *Pseudomonas* spp. and characterized by brown to black spots of various sizes, were also the most common defects observed in cauliflower stored at 2.5, 5, and 7.5°C (Lipton and Harris 1976). Black spotting affecting more than 2–5% of the curd surface area was also considered a limiting factor for cauliflower marketability during storage at 0.3°C plus simulated display for 2 additional days at 20°C (Ekman and Golding 2006). Yellowing and riciness also affected 8.0 and 5.5%, respectively, of the cauliflower shipments arriving to New York (Ceponis et al. 1987), but changes in color were negligible in cauliflower stored at 2.5 and 5°C after 19 days (Lipton and Harris 1976). Conversely, when cauliflower was stored at 1°C, yellowing of the curd limited its postharvest life to 25 days (Romo-Parada et al. 1989), and after 21 days at 4°C, the curd became less white and more yellow (lower L* values), while some brown discoloration was visually apparent (Berrang et al. 1990). Likewise, cauliflower stored at 7.5°C showed decreased L* values (less white) after 19 days (Lipton and Harris 1976).

Besides changes in the color of the curd, flavor also changes even when cauliflower is stored at recommended temperatures. For example, storage of cauliflower during 4 weeks at 0–1°C resulted in decreased sweet taste intensity, increased spicy taste, and off-odor and off-taste intensity, without major changes in bitter taste intensity (Gajewski and Radzanowska 2003).

Cauliflower weight loss increases during storage and is significantly affected by temperature. For example, while cauliflower stored at 1°C lost only 0.8% of its initial weight after 11 days and approximately 1.0% after 25 days (Romo-Parada et al. 1989), cauliflower stored in a domestic refrigerator (4–8°C) lost on average 2.0% of its initial weight after 7 days, while when stored under ambient conditions (12–22°C), weight loss doubled (4.6%) (Song and Thornalley 2007). A weight loss of 7% was considered to be the maximum acceptable before cauliflower becomes unacceptable for sale (Robinson et al. 1975).

Film wrapping has been successfully used to reduce moisture loss and improve overall cauliflower quality during handling, storage, and retail display. Weight loss of cauliflower wrapped in different types of films and stored at 1.5°C ranged from less than 0.01% to a maximum of 0.8% after 7 days, but increased to 0.1–1.72% after 2.5 additional days at 20°C (Artés and Martínez 1999). Similarly, cauliflower wrapped in sealed plastic film bags showed significantly less weight loss (0.2 and 0.5%, respectively) than nonwrapped cauliflower (14.7%) after storage for 23 days at 0–1°C. Furthermore, packaged cauliflower showed less end-scar discoloration and less curd browning than nonwrapped cauliflower (DeEll et al. 2003).

Changes in the compositional quality of cauliflower have also been reported, depending on storage time and temperature. Total sugar content of cauliflower decreased during the first 14 days of storage at 0°C, but no changes occurred afterward. Glucose levels declined, while fructose and sucrose contents did not change during storage. Glucosinolate content increased during storage of cauliflower after 28 days at 0°C but remained stable henceforward (Hodges et al. 2006). When stored in a domestic refrigerator (4–8°C) for 7 days total, cauliflower glucosinolate content decreased by about 11% (from initial value of 13.5–12.0 μmol/100 g fresh weight), yet when stored at ambient temperature (12–22°C) for 7 days, total glucosinolate content of cauliflower showed no significant decrease (Song and Thornalley 2007).

During storage at 2°C and 95–100% relative humidity, ascorbic acid content of cauliflower decreased from initial values of 82.63 mg/100 g to 79.98 mg/100 g fresh weight after 3 weeks, which corresponds to retention of about 97%. A strong correlation was found between initial ascorbic acid content and total sulfur content in cauliflower, suggesting that sulfur-containing compounds may be involved in ascorbic acid retention during storage (Albrecht et al. 1990). However, when stored at 20°C, initial ascorbic acid content of cauliflower was reduced by about 25% (from 48.6 to 36.5 mg/100 g fresh weight) after only 3 days of storage, which corresponded to the time that cauliflower was considered unacceptable for consumption (Wills et al. 1984).

Time and Temperature Effects on the Visual Quality of 'Fremont' Cauliflowers

'Fremont' white cauliflowers shown in Figures 6.23–6.27 were harvested at the mature stage, with firm and compact curds, from a commercial operation in the Orleans Island, Quebec, Canada, during the summer season (i.e., July). Promptly after harvest, fresh cauliflowers were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Changes in cauliflower curd and leaf coloration, wilting, and "riciness" are the major visual quality changes during storage of 'Fremont' cauliflowers. Cauliflowers stored at 0°C maintain acceptable visual quality during 20 days. After that, the curd appears less compact and less white than at harvest, while the leaves appear wilted. A yellowish discoloration also develops in some of the florets (Figure 6.23).

'Fremont' cauliflower stored at 5°C maintains acceptable visual quality during 10–12 days. However, after 12 days the curd appears less compact and less milky than at harvest, while the leaves appear wilted. A brownish discoloration develops in some of the florets, and the cut edges of the leaves appear less green and more yellow than at harvest (Figure 6.24).

Storage of cauliflower at 10°C results in loss of curd compactness and development of brownish spots. 'Fremont' cauliflower stored at this temperature maintains acceptable visual quality during 8 days, but afterward the curd appears less compact and less white than at harvest, while the leaves appear wilted. A brownish discoloration develops in some of the florets on day 10 (Figure 6.25). Simultaneously with changes in visual quality attributes, overall head firmness decreases and cauliflower becomes soft and spongy after 8 days.

'Fremont' cauliflower stored at 15°C maintains acceptable visual quality during 6 days. However, after 6 days, the curd appears less compact and less white than at harvest, while the leaves appear wilted. On day 8 a brownish discoloration develops in some of the florets (Figure 6.26). In addition, after 6–8 days, cauliflower feels very soft when gently squeezed.

Yellowing of the curd and development of brownish spots is rather faster in cauliflower stored at 20°C. On day 6, brown spots become visible and increase as storage progresses, and after 11 days, the dark spots increase in number and size. Simultaneously, the leaves around the cauliflower head change from a bright green color to a dull yellowish-green color and appear wilted (Figure 6.27). After 4–6 days, cauliflower feels very soft and spongy on touch.

In summary, 'Fremont' cauliflower stored at 0°C maintains better visual quality for longer periods of time (20 days) compared to storage at higher temperatures. Storage at 5, 10, 15, and 20°C reduces postharvest life of cauliflower to 12, 8, 6, and 4 days, respectively, due to wilting, yellowing of the curd and leaves, and development of black spotting.

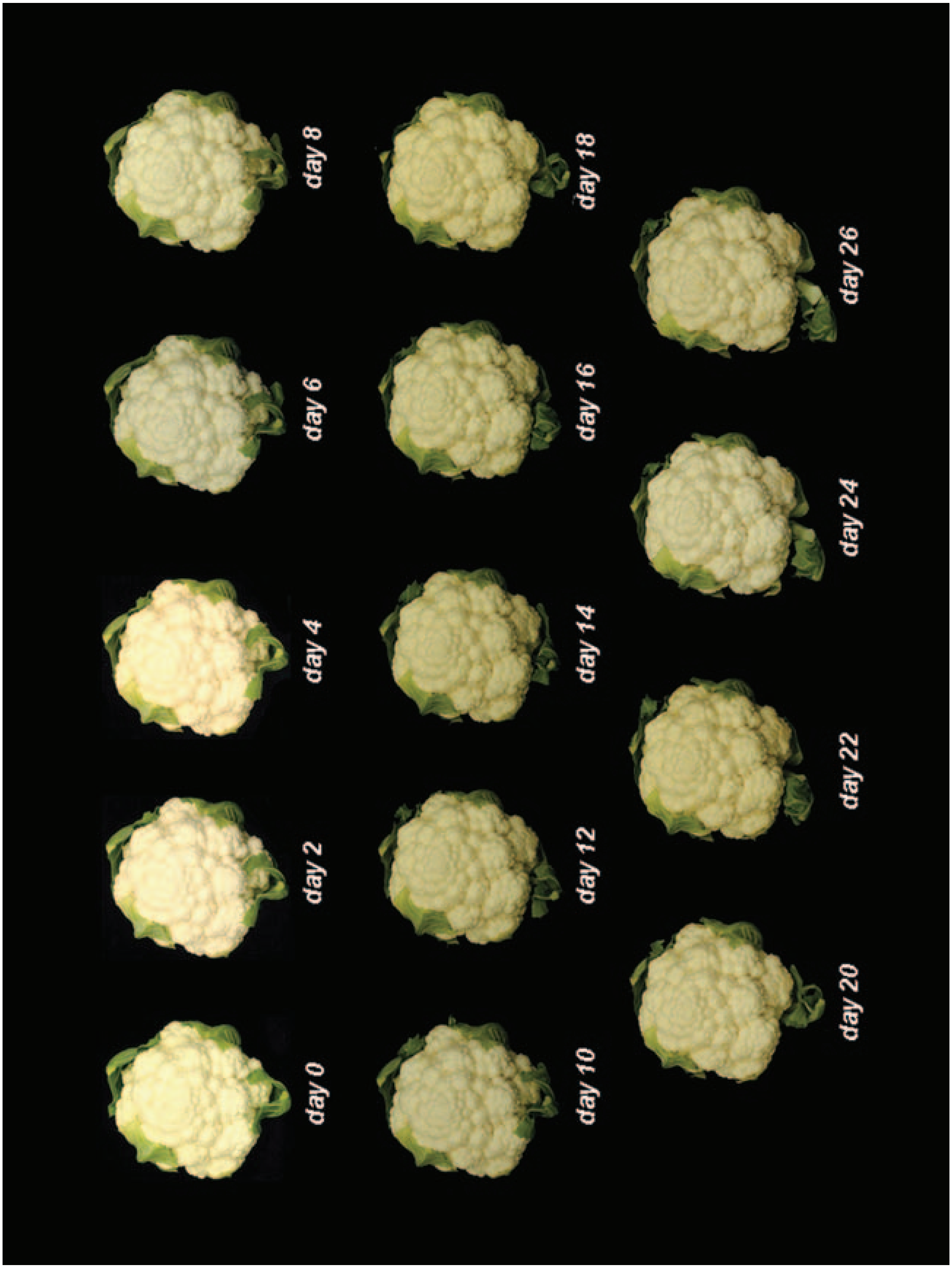
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Figure 6.23. Appearance of 'Fremont' cauliflower stored for 26 days at 0°C. Cauliflower maintains acceptable visual quality during 26 days. A yellowish discoloration develops in some of the florets during storage.

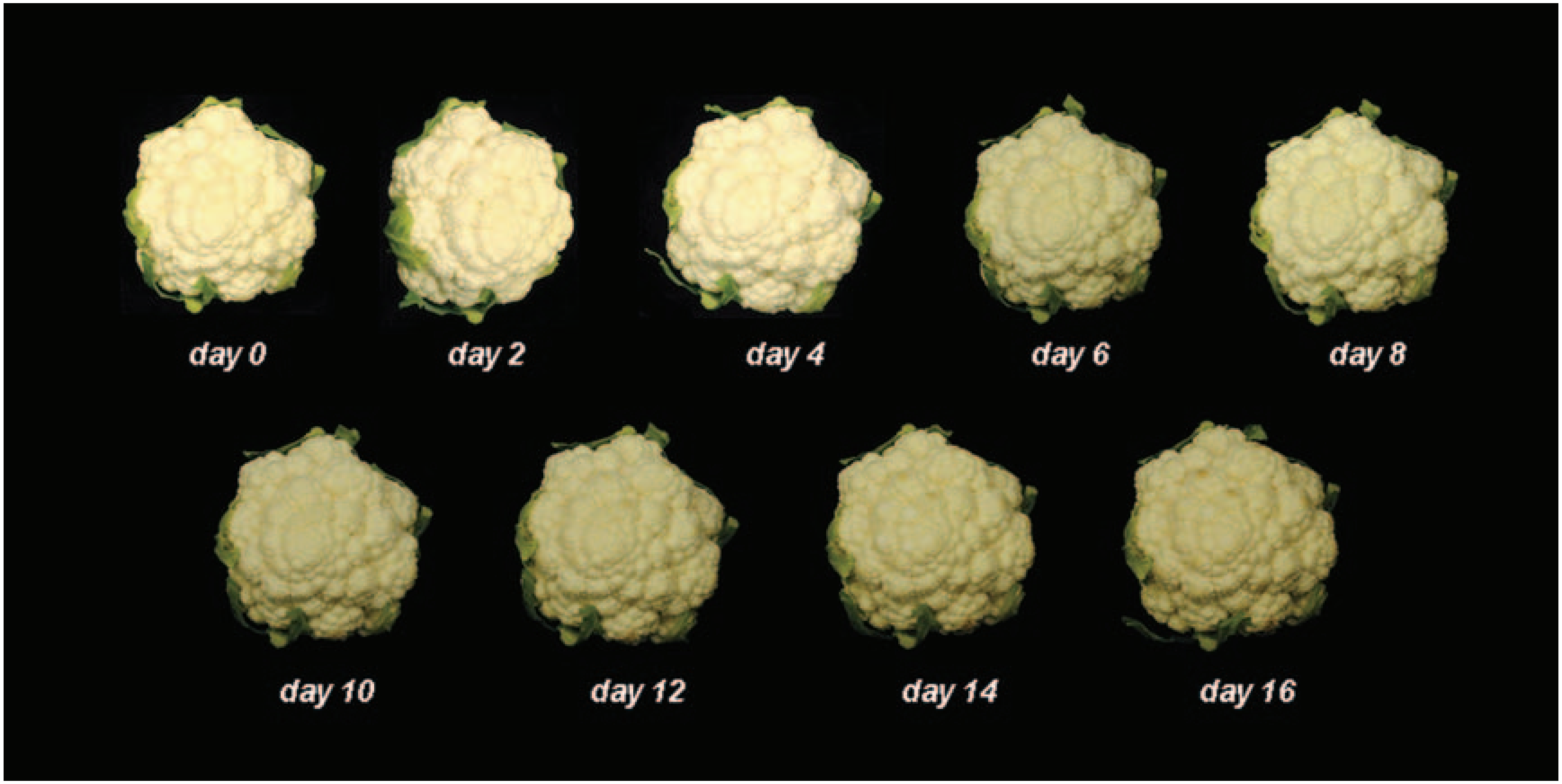
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Figure 6.24. Appearance of ‘Fremont’ cauliflower stored for 16 days at 5°C. Cauliflower maintains acceptable visual quality during 14 days. A brownish discoloration develops in some of the florets after 14 days.

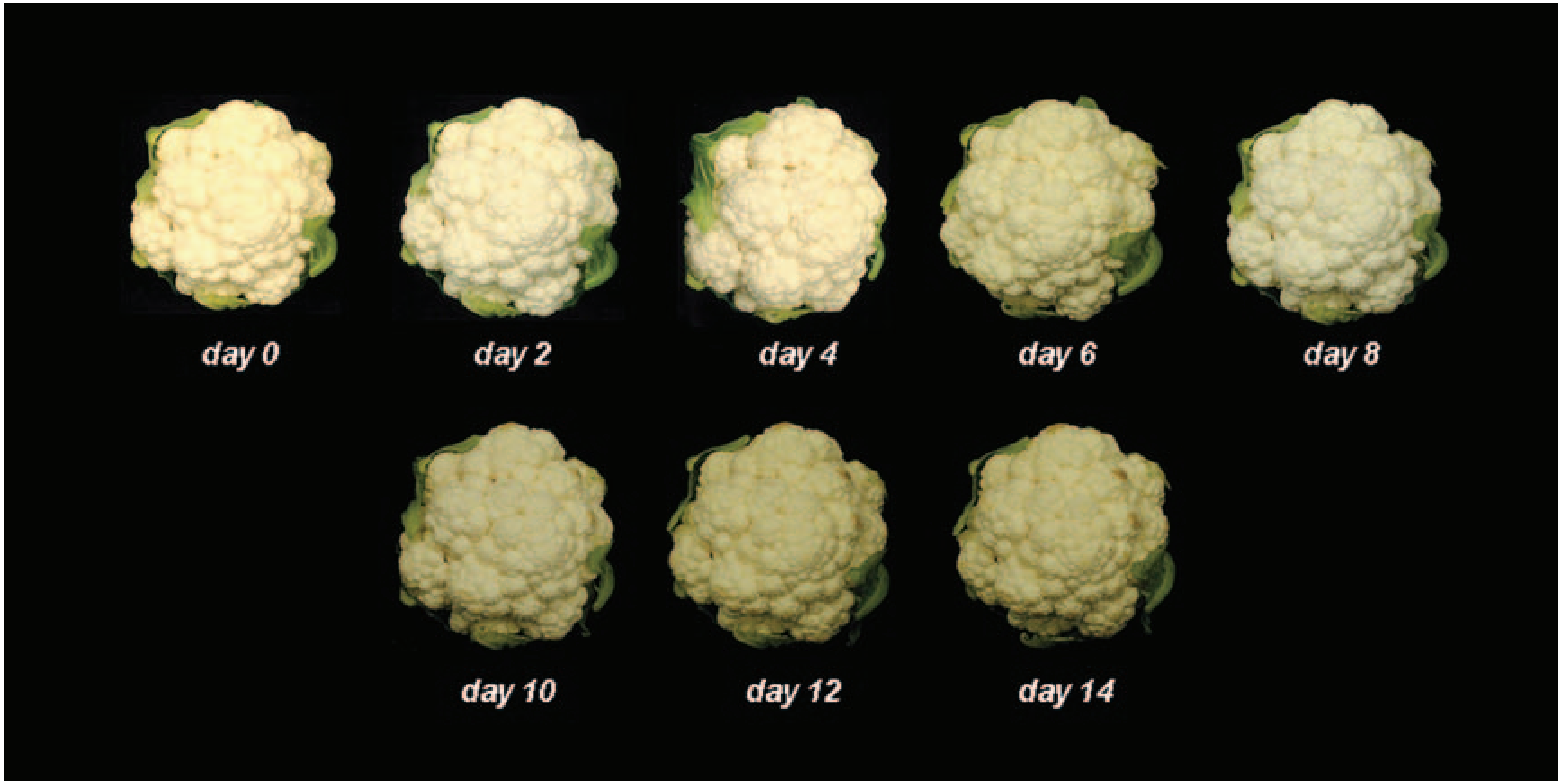
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Figure 6.25. Appearance of ‘Fremont’ cauliflower stored for 14 days at 10°C. Cauliflower maintains acceptable visual quality during 8 days. A brownish discoloration develops in some of the florets after 8 days.

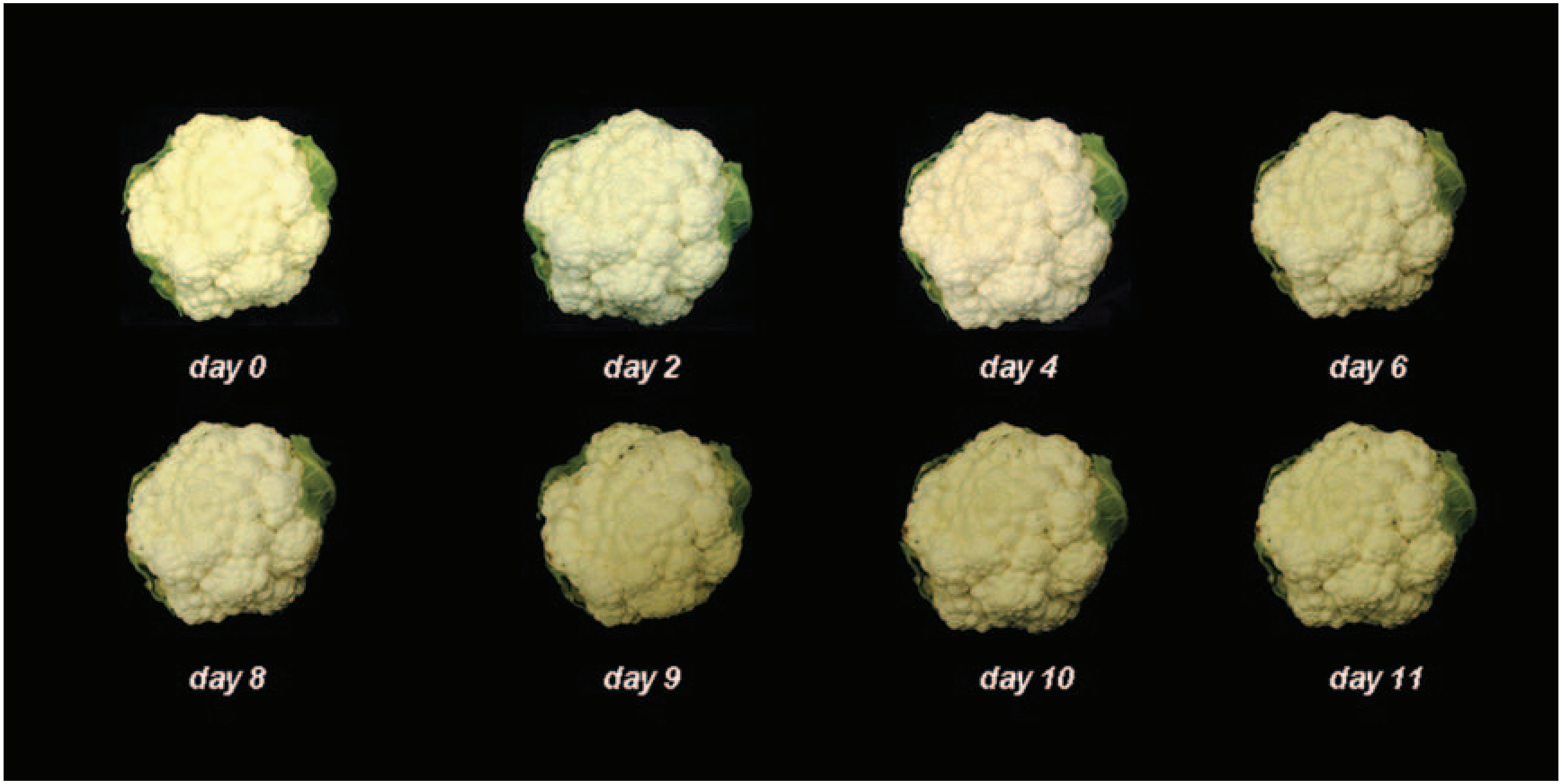
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Figure 6.26. Appearance of 'Fremont' cauliflower stored for 11 days at 15°C. Cauliflower maintains acceptable visual quality during 6 days. After 6 days, the curd appears less compact and less milky than at harvest, while the leaves appear wilted.

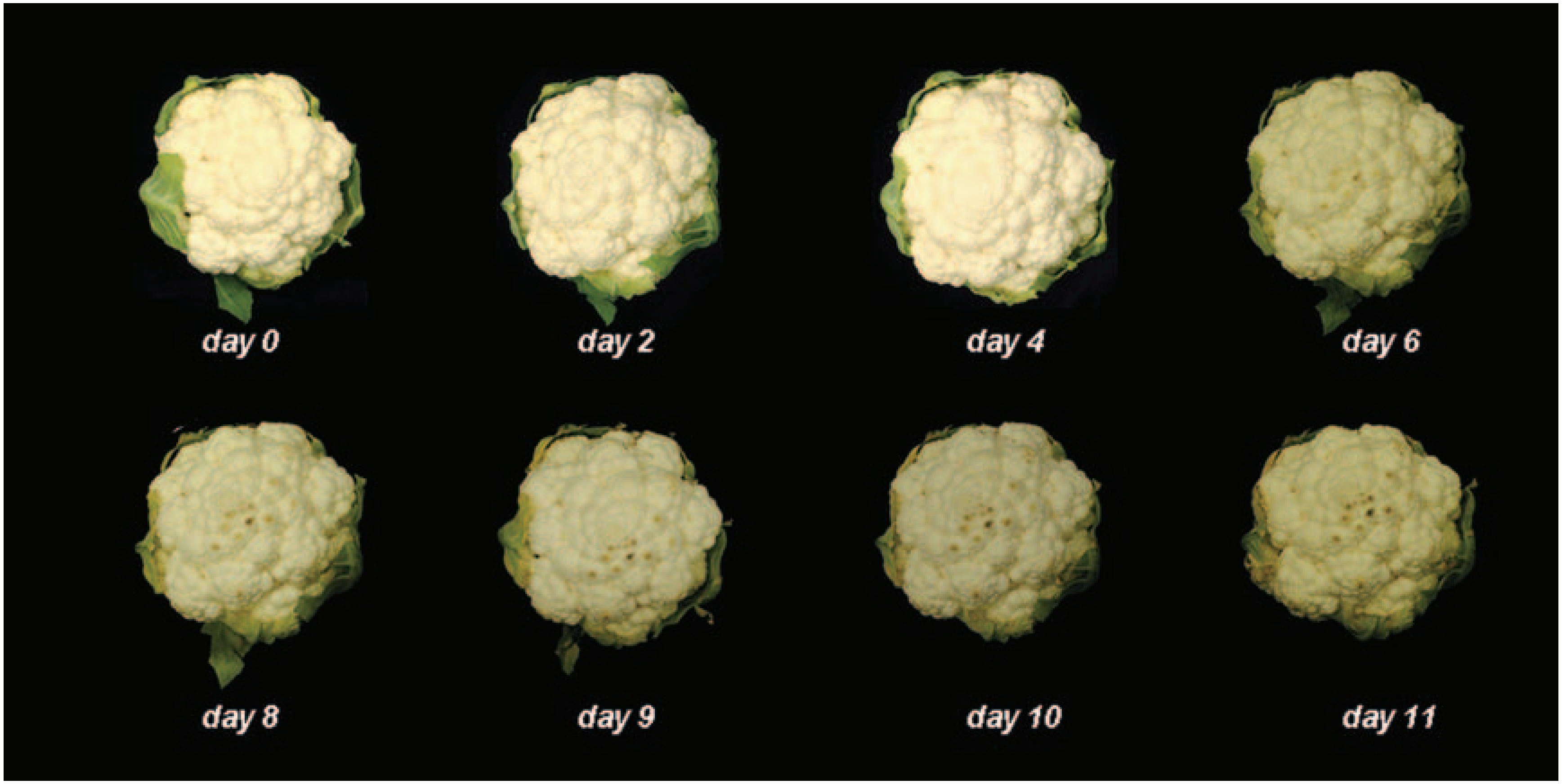
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Figure 6.27. Appearance of 'Fremont' cauliflower stored for 11 days at 20°C. Cauliflower maintains acceptable visual quality during 4 days. After 11 days the florets appear less compact, more yellowish, and covered with dark spots, while the leaves are severely wilted and yellowish.

BROCCOLI

Scientific Name: *Brassica oleraceae* L. var. *italica* Plecnk.
Family: Brassicaceae

Quality Characteristics

Broccoli, also known as calabrese or sprouting broccoli, is a cool-season vegetable, closely related to cauliflower. This brassica vegetable is believed to be native to the Mediterranean area and Asia Minor, and has been very popular in Italy since the Roman Empire. Broccoli is mostly grown for the clusters of unopened flower buds and tender flower stalks (Stephens 1994b; Toivonen and Forney 2004). The central head is usually harvested when still tight and compact, with no opened flowers (Stephens 1994b). A good quality broccoli should have a dark to bright green color with completely closed flower buds. Some broccoli cultivars may have a purplish-green color, which is not undesirable. The head should be firm to hand pressure, compact, and the stalk cleanly cut (Cantwell and Suslow 2007b; Ryall and Lipton 1979; Toivonen and Forney 2004). Loss of broccoli quality during storage usually results from wilting, yellowing of the buds and leaves, loosening or opening of the buds, and decay (Behrsing et al. 1998; Toivonen and Forney 2004).

Broccoli contains on average 88–89% water, 2.8% protein, 0.4% lipids, 6.6% carbohydrates, 1.7% total sugars, and 2.6% fiber (Albrecht et al. 1990; USDA 2006). The main sugars of broccoli are glucose (0.58–0.84 g/100 g fresh weight), fructose (0.7–0.93 g/100 g fresh weight), and sucrose (0.07–0.18 g/100 g fresh weight), with maltose (0.21 g/100 g fresh weight) and lactose (0.21 g/100 g fresh weight) present in smaller amounts (Schonhof et al. 2004; USDA 2006).

Broccoli is a very good source of vitamin C (ascorbic acid), containing on average 34–185 mg/100 g fresh weight, while broccoli leaves and stalks contain on average 93.2 mg ascorbic acid/100 g fresh weight (USDA 2006). Broccoli also contains about 99.65–142.69 mg sulfur/100 g fresh weight, which was suggested to be directly correlated with the initial content of ascorbic acid. That is, the higher the sulfur content the higher the ascorbic acid content (Albrecht et al. 1990, 1991). Sulfur-containing compounds were suggested to be involved in ascorbic acid retention in cruciferous vegetables, such as broccoli (Albrecht et al. 1990).

Total phenolic content of broccoli ranges from 34.5 to 337 mg/100 g fresh weight (Albrecht et al. 1991; Heimler et al. 2006; Podsedek 2007; Proteggente et al. 2002). Flavonol (7.12 mg/100 g fresh weight) and hydroxycinnamic conjugates (16.44 mg/100 g fresh weight) were the major phenolic components identified in broccoli (Heimler et al. 2006; Proteggente et al. 2002), while tannins (0.41 mg/g dry weight) comprised a smaller part of the phenolics (Heimler et al. 2006). Among the flavonoids, kaempferol (72 mg/kg fresh weight) and quercetin (30 mg/kg fresh weight) were the major flavonoid compounds found in broccoli (Hertog et al. 1992). Phenolic compounds together with vitamin C are the major antioxidants in broccoli, due to their high content and antioxidant activity (Heimler et al. 2006; Posedek 2007; Proteggente et al. 2002).

Broccoli contains glucosinolates compounds, which are responsible for the characteristic flavor of this vegetable. Although some of these compounds may have bitter tastes, they have been associated with beneficial anticarcinogenic properties (Verhoeven et al. 1977). Broccoli contains on average 1.20–6.24 μmol of glucosinolates/g fresh weight (Branca et al. 2002; Kushad et al. 1999; Schonhof et al. 2004; Song and Thornalley 2007; Valejjo et al. 2002). Glucoraphanin (7.1–29.4 μmol/100 g fresh weight) and glucoiberin (17.1 μmol/100 g fresh weight) were the major glucosinolates found in broccoli, with other glucosinolates found in minor amounts (Kushad et al. 1999; Song and Thornalley 2007). All together progoitrin, glucoiberin, glucoraphanin, glucobrassicin, and neo-glucobrassicin accounted for more than 95% of the total glucosinolate content in broccoli (Hansen et al. 1997). There is, however, a great variation in the glucosinolate content between broccoli genotypes (Brown et al. 2002; Jeffrey et al. 2003). For example, in florets of ten broccoli genotypes the total aliphatic glucosinolate content ranged from 3.6 to 24.1 mmol/g, glucoraphanin from 2.2 to 18.4 mmol/g, and the total indolyl glucosinates ranged from 1.0 to 4.9 mmol/g freeze-dried broccoli florets (Brown et al. 2002). Glucosinolate content affects the flavor of broccoli and, in general, consumers prefer broccoli that has a sweet, crisp, and characteristic broccoli flavor, rather than broccoli that has an intense bitter, pungent, and green or grassy flavor. Lower intensities of bitter and pungent flavors were associated with broccoli with glucosinolate content of 30–35 mg/100 g fresh weight or less (Brückner et al. 2005).

In addition, broccoli contains 327–705 UI vitamin A/100 g fresh weight, 242–538.9 μg β-carotene, 780–3,500 μg lutein plus zeaxanthin/100 g fresh weight, and 0.46–4.29 mg of α-tocopherol/100 g fresh weight (Bushway et al. 1986, 1989; Howard et al. 1999; Kurilich et al. 1999; Murcia et al. 2000; Noble 1967; Perrin and Gaye 1986; Podsedek 2007; Proteggente et al. 2002; USDA 2006; Vallejo et al. 2002; Vanderslice et al. 1990). Broccoli leaves are particularly rich in vitamin A (16,000 UI/100 g fresh weight) (USDA 2006).

Optimum Postharvest Handling Conditions

Broccoli should be promptly pre-cooled after harvest in order to maintain quality and extend postharvest life. A delay of cooling for 24 hours at 20°C before storage at 5°C reduced the shelf life of broccoli florets to about 9 days, compared to a maximum postharvest life of about 18 days when broccoli was immediately cooled after harvest (Xu et al. 2006). Although broccoli is commonly cooled by injecting liquid-ice into waxed cartons, hydro-cooling and forced-air cooling are also good options if adequate temperature and humidity can be maintained during transport (Ryall and Lipton 1979; Toivonen 1997; Toivonen and Forney 2004). Following pre-cooling, broccoli should be maintained at 0°C with 98–100% relative humidity (Cantwell and Suslow 2007b). Top icing during distribution is usually not necessary if the temperature can be maintained below 2°C with a high relative humidity (Tan et al. 1992). Under such conditions, expected postharvest life is about 2–4 weeks. However, if stored at 5°C, postharvest life of broccoli may be reduced to about 14–18 days, and at 10°C to about 5–9 days (Cantwell and Suslow 2007b; Xu et al. 2006). Postharvest life of broccoli stored at 20°C is reduced to less than 2 days due to loss of green color or development of decay (Ku and Wills 1999).

Hydro-cooling, combined with application of micro-perforated film wraps and cold storage at 1°C, has been shown to help maintain firmness and color in broccoli during retail display (Toivonen 1997). At the retail level, broccoli should be displayed in refrigerated cabinets equipped with a forced-air unit in order to delay losses in chlorophyll and ascorbic acid contents and to retain green color (Perrin and Gaye 1986). However, the uneven distribution of high temperatures very often encountered inside some consumer refrigerated displays (i.e., 8–11.2°C, depending on the position in the display), combined with high flow rates of air, may drastically reduce the quality and retail display life of non-wrapped broccoli to about 6 hours (Nunes et al. 1999).

Temperature Effects on Quality

Losses in green color, yellowing, and wilting are the most striking changes that occur in the visual quality of broccoli after harvest, usually limiting its postharvest life. Color changes in broccoli during storage are associated with an increase in L* (brightness) and chroma values and decrease in hue angle and chlorophyll content, as a result of yellowing of the florets (DeEll and Toivonen 1999; Gnanasekharan et al. 1992; Hyodo et al. 1995; Kasai et al. 1998; King and Morris 1994; Serrano et al. 2006; Zhuang et al. 1997). Although depending on the cultivar, there might be some variation related to the onset of yellowing, this process is greatly affected by temperature and may occur within a few days if broccoli is held under ambient temperatures (Costa et al. 2005; Hyodo et al. 1995; Kasai et al. 1998; King and Morris 1994; Toivonen and Sweeney 1998).

In an earlier study, yellow bud clusters (53.7%), enlarged buds (21.6%), and yellowing (13.5%) were the most common disorders, followed by bacterial soft rot (12.8%) and dark discoloration (6.0%) reported for broccoli shipments arriving to the New York market (Ceponis et al. 1987). Although the rate of yellowing and loss of chlorophyll is very fast during storage of broccoli at ambient temperature (20°C), as storage temperature decreases the rate of yellowing is significantly delayed, resulting in extended postharvest life (Kasai et al. 1998). While broccoli stored continuously at 0.3°C showed slight yellowing of the florets after 3 weeks, yellowing increased significantly after 2 additional days at 20°C (Ekman and Golding 2006). Similarly, broccoli stored at 4°C retained its green color and fresh appearance during 7 days, whereas broccoli stored at 20°C showed traces of yellowing after 3 days, and after 7 days the heads were completely yellow, showed some mold development, and released an unpleasant odor (Rangkadilok et al. 2002). A 2-day exposure at 20°C and 70–75% relative humidity following storage for 6 weeks at 1°C resulted in a complete loss of broccoli due to yellowing in 100% of the heads and development of decay in 20% of the heads (Tan et al. 1992). Dramatic changes in the green color were observed when broccoli was held at 37°C for 12 days compared to storage at 4°C. After 2 days at abuse temperature, there was a switch from positive to negative a* values, which corresponded to a decrease in hue values from about 130–80°, translated by a markedly visual change in color from green to yellow (Gnanasekharan et al. 1992).

Yellowing of the florets follows major physiological changes that occur during the postharvest period and that contribute to broccoli senescence (King and Morris 1994; Page et al. 2001). While yellowing of the broccoli florets initiated between 48 and 72 hours at 20°C, initial contents of soluble sugar, sucrose, starch, and organic acid were reduced by more than 50% or completely depleted after only 24 hours at 20°C (King and Morris 1994; Pogson and Morris 1997). After 10 weeks at 1°C, sugar content of broccoli was completely depleted (Pogson and Morris 1997). Chlorophyll content in broccoli stored at 1°C decreased sharply from initial values of about 4 mg to 1.11 mg/g dry weight after 20 days (Serrano et al. 2006). A marked decrease (80%) in the chlorophyll content was also observed in broccoli stored for 10 days at 20°C, while chlorophyll content of broccoli stored at 5°C decreased slightly after 1 day of storage and then remained practically unchanged henceforward (Starzynska et al. 2003). Decreases in chlorophyll content of broccoli stored at 0°C ranged from 20 to 25% after 30 days of storage, while in broccoli stored at 5°C initial chlorophyll content decreased by about 85% after 25 days. In broccoli stored at 10°C, chlorophyll content showed the greatest decrease (about 90%) after 40 days (Ren et al. 2006). Chlorophyll content in broccoli stored at 20°C showed a rapid decline, decreasing by more than 50% after 4 days (Costa et al. 2005; Pogson and Morris 1997). After 6 days, chlorophyll content of broccoli stored at 20°C decreased by more than 90%, with broccoli florets showing rapid yellowing between day 4 and 5 (Page et al. 2001).

Hot-water or -air treatments applied to broccoli immediately after harvest have been successfully used to retard yellowing of the florets during subsequent cold storage (Costa et al. 2005; Forney and Jordan 1998; Tian et al. 1996). However, some heat treatments using high temperatures and long exposure times may result in water-soaking of the tissues, increased production of off-odors, and susceptibility to decay due to heat damage (Forney and Jordan 1998; Tian et al. 1996). A heat treatment at 47°C during 7.5 minutes was considered one of the best hot-water treatments, as it reduced broccoli hue angle values to less than 2.5% after subsequent storage for 72–102 hours at 20°C (Tian et al. 1996), whereas immersion of broccoli in 50°C for 2 minutes reduced yellowing and decay without inducing off-odors or accelerating weight loss during subsequent storage at 20°C (Forney 1995). Furthermore, a hot-air treatment at 48°C for 3 hours delayed chlorophyll and decreased total sugar losses during subsequent storage at 20°C (Costa et al. 2005). On the other hand, hot-water treatments of 52°C for 3 minutes caused visual damage to broccoli flower buds and induced a nontypical "floral-like" odor and off-flavors (Forney 1995; Forney and Jordan 1998).

Weight loss increases during storage of broccoli regardless of the storage temperature, and in general, broccoli becomes unacceptable for sale when weight loss attains 4% (Robinson et al. 1975). Loss of water during storage of broccoli is strongly associated with the florets, with initial signs of wilting developing in that same region. During the first 24 hours of storage at 20°C, broccoli heads lost 75% of their water content through the florets and only 5% through the cut-end (Heyes et al. 2001). Protective packaging may prevent excessive weight loss during storage, while helping maintain acceptable quality during longer periods after harvest (Albrecht et al. 1990; Ren et al. 2006; Serrano et al. 2006; Zhuang et al. 1997). Weight loss of nonpackaged broccoli stored at 1°C and 90% relative humidity reached values higher than 45% after 20 days of storage, while in broccoli packaged in plastic films weight loss averaged 7% after 28 days at 1°C (Serrano et al. 2006). Weight loss of six different broccoli cultivars stored at 2°C and 95–100% relative humidity was on average 1.73% after 3 weeks of storage (Albrecht et al. 1990). In broccoli stored under domestic refrigeration conditions (4–8°C), weight loss was about 1.4% after only 7 days, while when held at ambient temperatures (12–22°C), weight loss increased to 9.0% (Song and Thornalley 2007). During storage at 4°C for 21 days, weight loss was about 2%, but it doubled to approximately 4% after transfer to 20°C for 2 additional days (Paradis et al. 1995). Weight loss was significantly higher in nonpackaged compared to packaged broccoli, and increased with increased temperature and storage time. After 30 days, weight loss in broccoli stored at 0°C attained 1 and 5% in packaged and nonpackaged broccoli, respectively, while after 25 days of storage at 5°C weight loss in packaged and nonpackaged broccoli was about 1.5 and 17%, respectively. Weight loss significantly increased in nonpackaged broccoli stored at 10°C, and after 10 days broccoli had already lost 22% of its initial weight, compared to a 2% weight loss in packed broccoli (Ren et al. 2006).

Changes in the ascorbic acid content of broccoli during storage are greatly associated with storage time, temperature, and humidity of the surrounding environment. Ascorbic acid content in broccoli stored at 1°C decreased progressively during storage, from initial values of 2.15 mg/g dry weight to minimum values of 1.45 mg/g dry weight after 20 days of storage (Serrano et al. 2006). Besides, depending on the broccoli cultivar, ascorbic acid retention ranged from 45.99 to 98.13% after 3 weeks of storage at 2°C (Albrecht et al. 1990). In some cultivars stored at 2°C and 95–100% relative humidity for 3 weeks, ascorbic acid content decreased by only 2% (106.94–104.94 mg/100 g fresh weight) or 4% (from 114.3 to 110.01 mg/100 g fresh weight), while in others it decreased by 54% (from 126.57 to 58.21 mg/100 g fresh weight) (Albrecht et al. 1990, 1991). When broccoli was stored at 4°C for only 5 days, ascorbic acid content decreased by about 21% (from 134 mg/100 g to 106 mg/100 g fresh weight) (Vanderslice et al. 1990). In the latter case, major losses occur during the first 24 hours of storage, and then ascorbic acid levels remain quite stable if kept at 4°C for the next 3 days (Vanderslice et al. 1990). Similarly, ascorbic acid content of broccoli decreased rapidly in the first 3 days of storage at 4°C, remaining quite stable afterward. Thus, the average retention of ascorbic acid ranged from 52 to 87% after 3 weeks at 4°C, depending on the year of harvest (Howard et al. 1999). When broccoli was held at 20°C, ascorbic acid content decreased from initial value of 75.7 mg/100 g to 32.3 mg/100 g fresh weight after only 4 days of storage, which corresponded to a decrease of approximately 57% of the initial content (Wills et al. 1984). The rate of ascorbic acid content loss in broccoli stored at 20°C was 8% per day during 7 days, and only 44 and 28% of the initial ascorbic acid content was retained after 7 and 14 days, respectively. However, when stored at 4°C the ascorbic acid retention was much higher, with practically no losses after 7 days and with a 20% loss after 14 days (Favell 1998). Conversely, ascorbic acid content increased by about 4 or 8% after 5 hours at 20–25°C, remained constant during 3 subsequent days at 4°C plus 2 days at 10–16°C, and then decreased after 4 days at 10–16°C, while no significant changes were observed in β-carotene content of broccoli handled likewise (Wu et al. 1992). Similarly, ascorbic acid content of broccoli stored for 21 days at 4°C remained quite constant during storage, decreasing significantly after transfer to 20°C for 2 additional days, while carotenoid content remained quite stable throughout the whole storage and simulated display period (Paradis et al. 1995). On the other hand, total carotenoid content decreased significantly in broccoli stored at 5°C for 6 days, with a significant reduction occurring after 2 days of storage (Barth and Zhuang 1996).

The use of mist during retail display may help to significantly reduce the loss of moisture as well as to preserve the initial chlorophyll and ascorbic acid contents of broccoli (Barth and Zhuang 1996; Barth et al. 1990, 1992; Mohd-Som et al. 1995; Zhuang et al. 1995). While in nonmisted broccoli, moisture loss reached about 5–7% after only 72 hours at 18°C, misted broccoli lost only about 0.2–1.8% from its initial weight (Barth et al. 1990, 1992). Moisture content decrease was also higher in nonmisted compared to misted broccoli during storage for 5 days at 4°C. After 4 days misted broccoli had lost about 3% of its initial weight, while nonmisted broccoli had a weight loss that ranged from 1.3 to 3% (Mohd-Som et al. 1995). Similarly, weight loss in misted broccoli stored for 6 days at 5°C was about 5% of the initial weight, while vented packaged and nonmisted unpacked broccoli attained a 13 and 22% weight loss, respectively. Consequently, ascorbic acid content of nonmisted unpacked broccoli was reduced by 80% after 6 days at 5°C, while a smaller decrease (about 25%) was observed in misted broccoli (Barth and Zhuang 1996). Similarly, nonmisted broccoli lost about 42.5–61.3% of its initial ascorbic acid content, whereas misted broccoli lost 26–36% of its initial ascorbic acid content (Barth et al. 1990, 1992). Furthermore, higher chlorophyll retention was also observed in misted (about 80–90% retention) compared to nonmisted broccoli (about 26–50% retention), with misted broccoli appearing significantly greener than nonmisted (Barth et al. 1992; Zhuang et al. 1995). Higher ascorbic acid losses in nonmisted broccoli were associated with the alteration of cellular integrity due to dehydration and consequently with the increased degradation of ascorbic acid by oxidase enzymes (Barth et al. 1990).

Total phenolic content of broccoli increased from 56.2 to about 76.0 mg/100 g fresh weight after 3 days of storage at 20°C, which corresponded to an increase of about 35%. In nonpackaged broccoli stored at 5°C, initial phenolic content increased from 56.2 to 71.2 mg/100 g, while in packaged broccoli phenolic content remained practically unchanged after 7 days of storage (Leja et al. 2001; Starzynska et al. 2003). The higher total phenolic content obtained for nonpackaged compared to packaged broccoli samples might have resulted from loss of water during storage and solute concentration. In fact, a sharp decrease in the total phenolic content on a dry weight basis from about 26 mg/g to about 16 and 23 mg/g dry weight was observed during storage of nonpacked and packed broccoli, respectively, after 20 days of storage at 1°C (Serrano et al. 2006).

Changes in the total and individual glucosinolate content of broccoli are greatly dependent on the storage time and temperature. For example, total glucosinolates content of broccoli decreased by 27% after 7 days at domestic refrigerated temperatures (4–8°C), while no major changes were found in the glucosinolates content of broccoli held at ambient temperature (12–22°C) (Song and Thornalley 2007). Conversely, the highest decrease (about 64–79%) in total glucosinolate content was observed when fresh broccoli was left at room temperature (20°C) for 5 days, compared to a 4–16% decrease in broccoli held in a refrigerator at 4°C. More specifically, glucoraphanin content of broccoli florets decreased by 82% after storage for 5 days at room temperature (20°C), whereas in broccoli stored in a refrigerator (4°C), it decreased by only 31% (Rodrigues and Rosa 1999). Storage at 10°C significantly reduced the glucoraphanin content in broccoli after 9 days of storage, compared to 0 or 5°C. Glucoraphanin content increased by 32, 20, and 2% after 6 days in broccoli stored at 0, 5, and 10°C, respectively. However, after 12 days the glucoraphanin content of broccoli stored at 0 and 5°C decreased by 2 and 23%, respectively, while the greatest decrease (60%) was observed in broccoli stored at 10°C after 9 days (Xu et al. 2006). After 21 days of storage at 4°C, sulforaphane decreased by about 50–55%, with the greatest decrease occurring during the first 7 days of storage (Howard et al. 1997). Similarly, a 56% decrease in glucoraphanin content of 'Marathon' broccoli stored in plastic bags was observed after 3–7 days at 20°C, while in broccoli stored in open boxes the decrease in glucoraphanin attained 55% after only 3 days at 20°C. In contrast, there were no significant changes in the glucoraphanin content of broccoli stored in plastic bags or open boxes during 7 days at 4°C (Rangkadilok et al. 2002). Consequently, the most important conditions necessary to avoid reduction of glucosinolate content in broccoli, which are also those conditions that maintain overall quality, should be storage at temperatures below 4°C and high relative humidity. High humidity levels in the surrounding atmosphere help to maintain cellular integrity and prevent glucosinolate enzymatic degradation (Jones et al. 2006; Rangkadilok et al. 2002).

Time and Temperature Effects on the Visual Quality of 'Packman' Broccoli

'Packman' broccoli shown in Figures 6.28–6.34 was harvested with firm heads and closed florets, from a commercial operation in the Orleans Island, Quebec, Canada, during the summer season (i.e., July). Promptly after harvest, fresh broccoli was stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

The most important changes in the visual quality attributes of 'Packman' broccoli during storage are associated with loss of green color and increased development of yellowing, which increases as storage time and temperature increase. Changes in the color of the florets occur before any major signs of wilting or loss of head compactness are apparent, particularly at temperatures higher than 5°C, where color changes are remarkably fast, and limit the postharvest life of broccoli. ‘Packman’ broccoli stored at 0°C maintains acceptable visual quality during 20 days, with only a subtle yellowish-brown discoloration being perceptible after 14 days of storage in some of the florets on the central part of the broccoli head. The remaining broccoli leaves attached to the head of broccoli lose their initial turgidity and after 10 days they become less stiff, drop, and appear wilted (Figures 6.28 and 6.29).

‘Packman’ broccoli stored at 5°C maintains acceptable quality during 10 days, yet after 4 days the leaves that remained attached to the head of broccoli appear less turgid and more wilted than at harvest. After 14 days, the stalk appears dry with some brownish discoloration developing on the cut surface area (Figure 6.30). After 10 days, a markedly yellowish-brown discoloration develops in some of the florets, which increases as storage progresses (Figure 6.31).

Yellowing of the florets is very fast in ‘Packman’ broccoli stored at 10°C, and after only 3 days some of the florets develop a yellowish-green color, which increases as storage progresses. After 5 days, most of the broccoli florets appear greenish-yellow and opened, while the stalk appears less bright green than at harvest (Figure 6.32).

Color of the broccoli florets changes very quickly from a dark green to yellowish color in only few days of storage at 15°C. After 2 days, some of the florets become greenish-yellow, while some others show a brownish discoloration. Yellowing increases very quickly as storage progresses, and after 5 days the color of all the broccoli florets is of a yellowish-gold. Yet the leaves and stalk remain green (Figure 6.33) and quite firm.

After only 1 day ‘Packman’ broccoli florets stored at 20°C already show some yellowish discoloration. After 3 days, the floret color appears a deep yellowish-gold, and some of the florets at the extremities of the broccoli head are also completely opened. Yet the leaves and stalk remain quite green and turgid (Figure 6.34).

Overall, ‘Packman’ broccoli stored at 0°C maintains a better visual quality for longer periods of time (14 days), compared to storage at higher temperatures. Broccoli stored at 5°C maintains acceptable quality during 10 days, whereas postharvest life of broccoli stored at 10, 15, and 20°C is reduced to only 3, 2, and 1 days, respectively, due to yellowing of the florets.

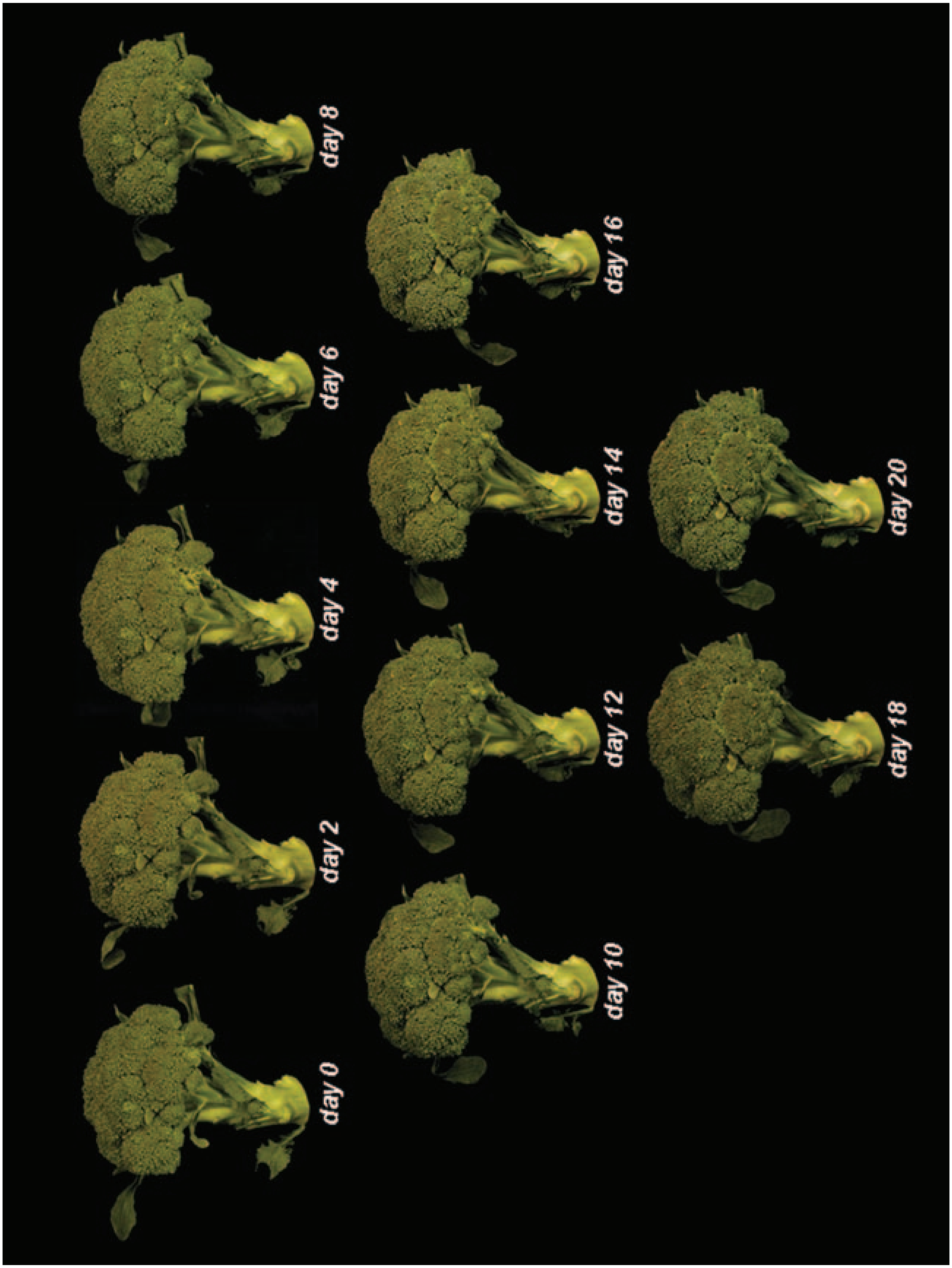
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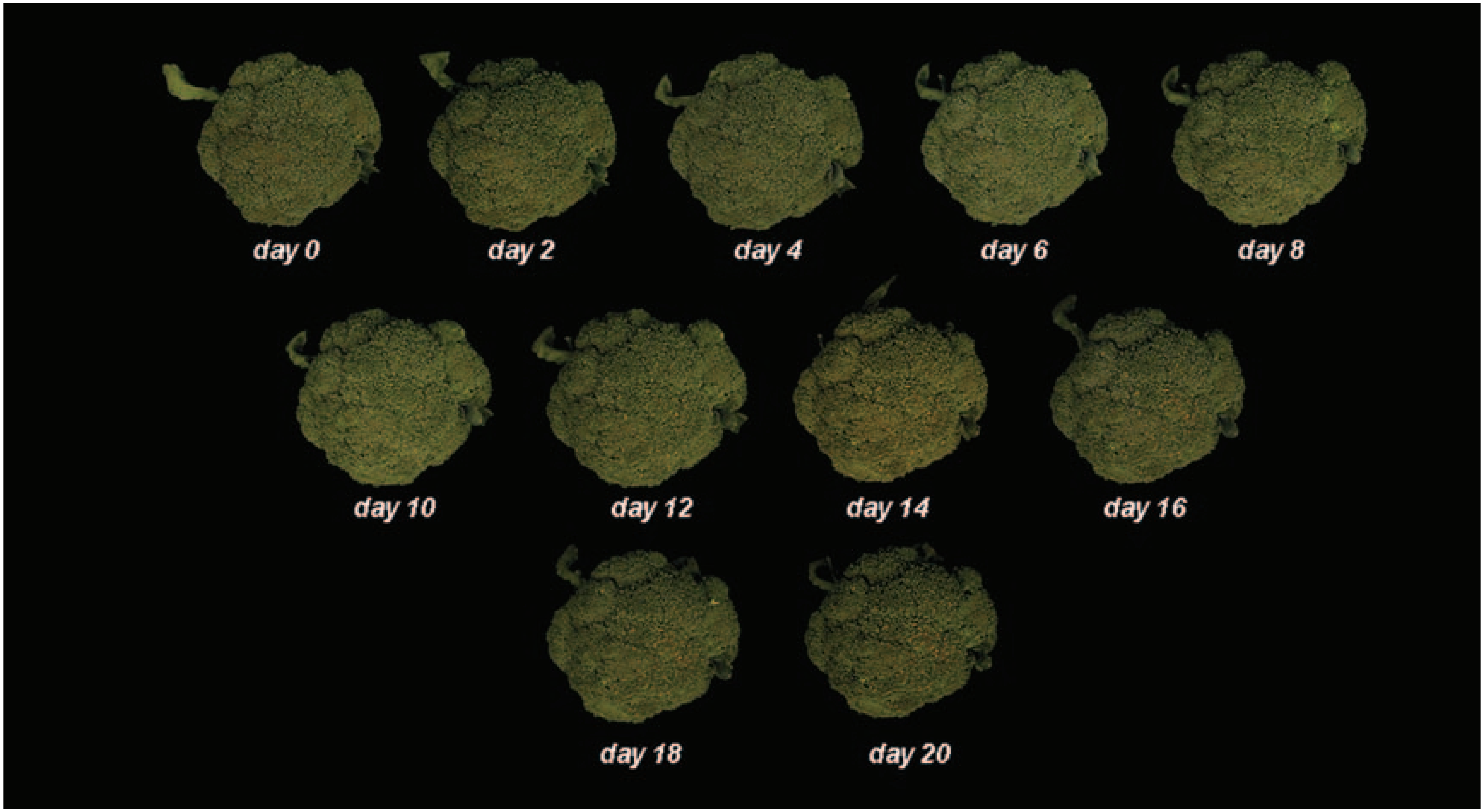
Figure 6.28. Appearance of ‘Packman’ broccoli stem, florets, and leaves stored for 20 days at 0°C. Broccoli maintains acceptable visual quality during 14 days.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day 20

Figure 6.29. Appearance of 'Packman' broccoli florets stored for 20 days at 0°C. After 14 days a subtle yellowish-brown discoloration is noticeable in some of the florets.

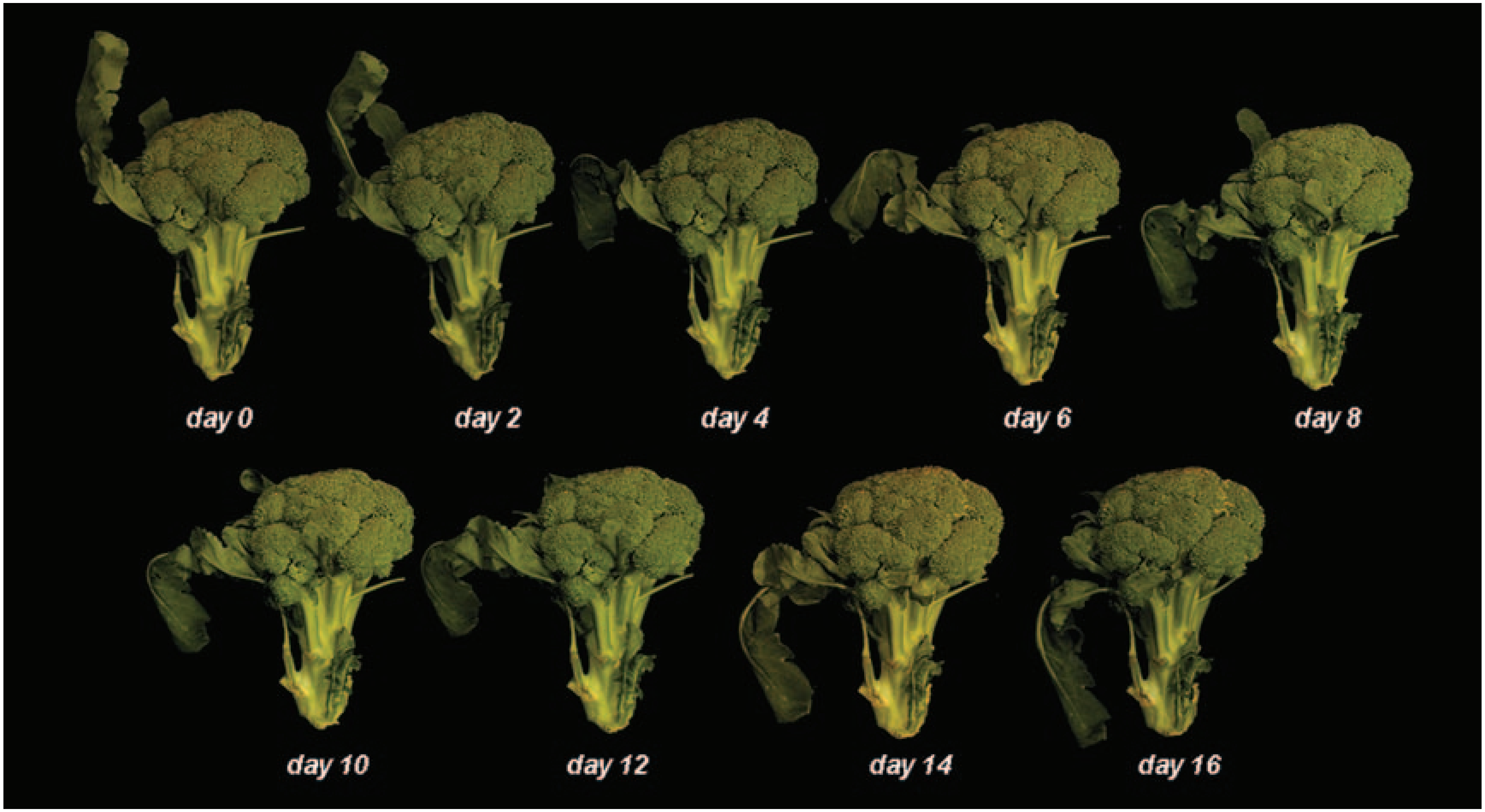
day 0
day 2
day 4
day 6
day 8
day 10
day 12
day 14
day 16

Figure 6.30. Appearance of ‘Packman’ broccoli stem, florets, and leaves stored for 16 days at 5°C. Broccoli maintains acceptable visual quality during 10 days.

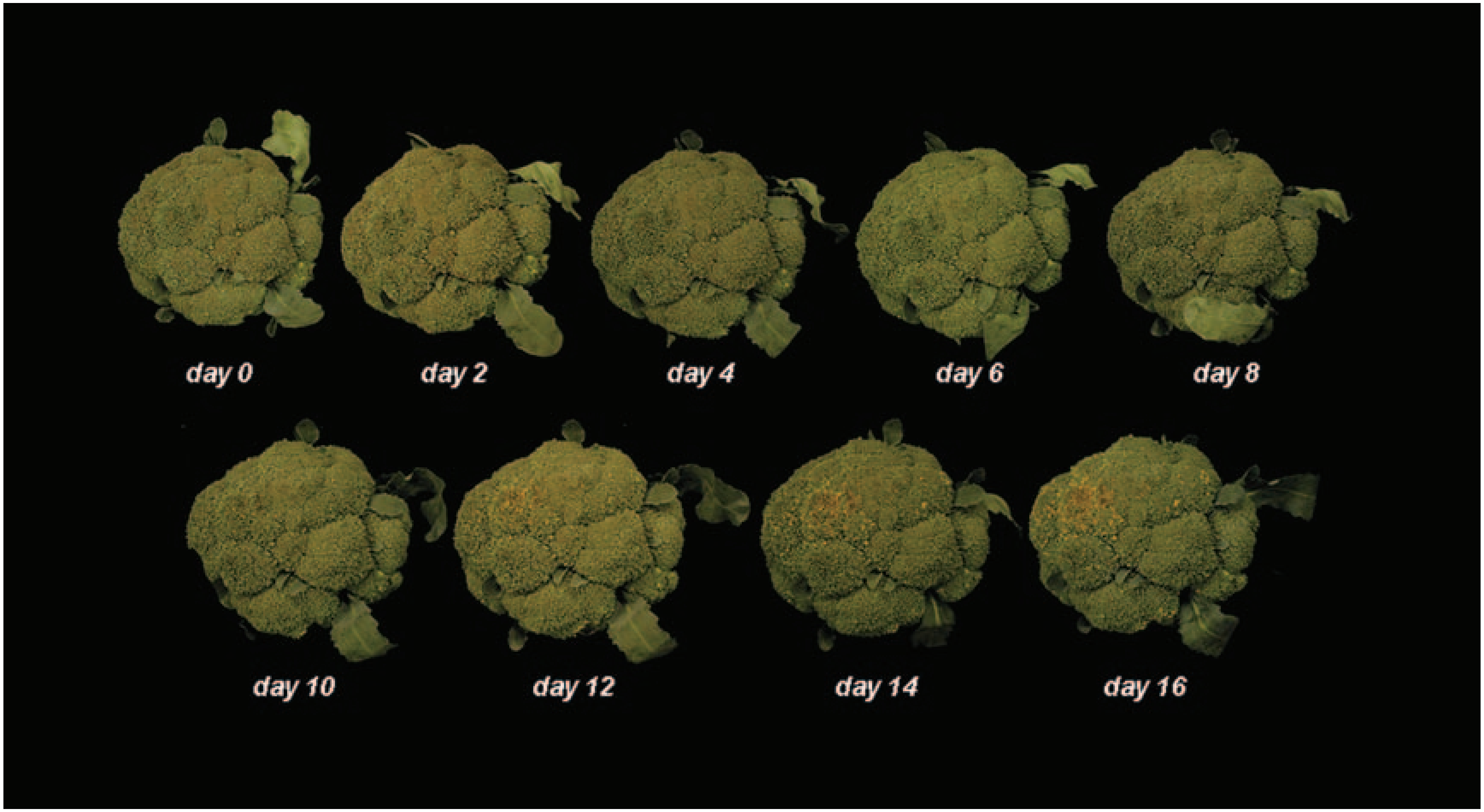
day 0
day 2
day 4
day 6
day 8
day 10
day 12
day 14
day 16

Figure 6.31. Appearance of 'Packman' broccoli florets stored for 16 days at 5°C. After 10 days a markedly yellowish-brown discoloration develops in some of the florets.

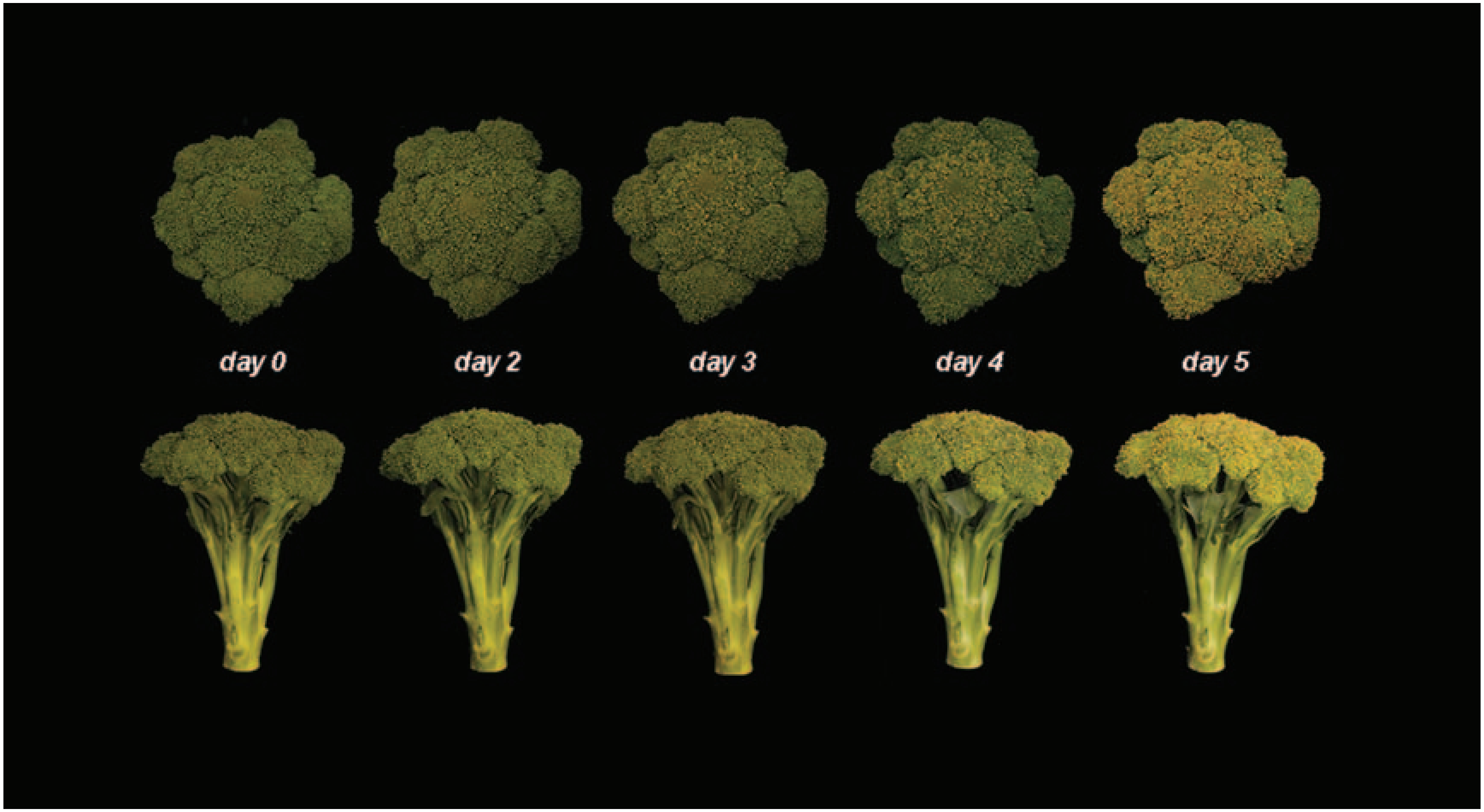

Figure 6.32. Appearance of 'Packman' broccoli stored for 5 days at 10°C. Broccoli maintains acceptable visual quality during 3 days. After 5 days most of the florets appear greenish-yellow.

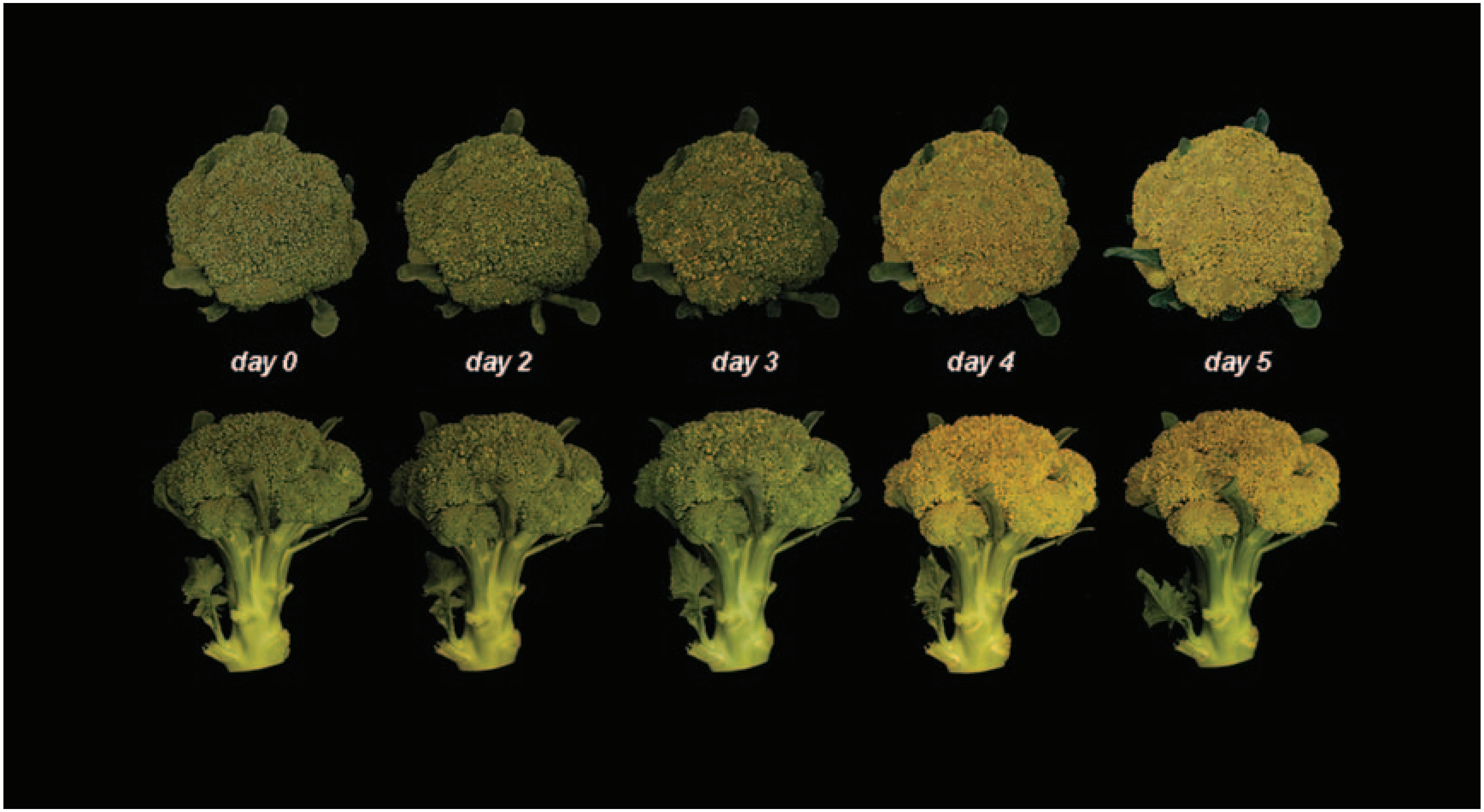
day 0
day 2
day 3
day 4
day 5

Figure 6.33. Appearance of 'Packman' broccoli stored for 5 days at 15°C. Broccoli maintains acceptable visual quality during 2 days. After 4 days all the florets have a yellowish-gold coloration.

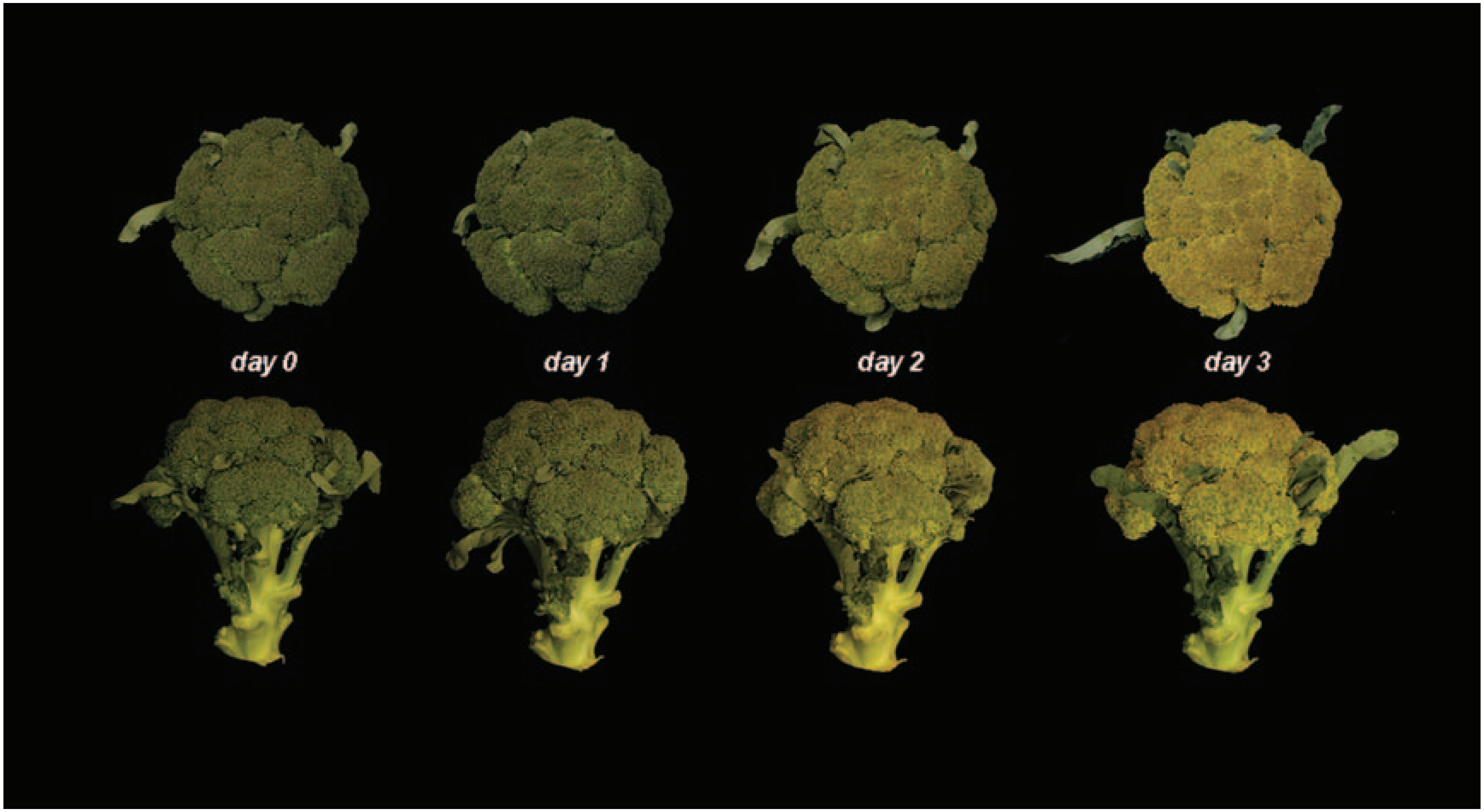

Figure 6.34. Appearance of 'Packman' broccoli stored for 3 days at 20°C. Broccoli maintains acceptable visual quality during 1 day. After 3 days all the florets have a deep yellowish-gold coloration.

BRUSSELS SPROUTS

Scientific Name: *Brassica oleraceae* L. var. *gemmifera* Zenk.
Family: Brassicacea

Quality Characteristics

Brussels sprouts are native to cool regions of northern Europe and were a very popular vegetable in Belgium during the sixteenth century. They got their name after Brussels, the capital of Belgium, and from Belgium they spread throughout temperate Europe. With the French settlers of Louisiana the culture of this miniature cabbage was then spread to North America (Mills 2001; Stephens 1994c).

Brussels sprouts are a tall-stemmed cabbage in which many compact tiny buds develop at the base of the leaves along the entire tall central stalk of the Brussels sprouts plant (Stephens 1994). While in Europe the preferred size for Brussels sprouts is about 1–1.5 cm; in North America larger sprouts with 2.5–5 cm are preferred over smaller ones (EEC 1987; Mills 2001). In general, good quality Brussels sprouts should be about 1–2.5 cm in diameter (i.e., 1–1.5 cm in Europe and 2.5 cm in North America), have a fresh appearance and bright green and closed outer leaves, and should be firm. Yellowing indicates advanced senescence and loss of quality, while wilted or puffy sprouts tend to be woody in texture and have objectionable flavors. In cross section, inner leaves should be light yellow, arranged quite tightly and without large air pockets between them (EEC 1987; Forney and Toivonen 2004a; Mills 2001; Ryall and Lipton 1979). Brussels sprouts should have a sweet and mild flavor when cooked, while bitterness is associated with high concentration of certain glucosinolates such as sinigrin and progoitrin (Cantwell and Suslow 2007a; van Doorn 1999).

Brussels sprouts contain on average 84–86% water, 3.4% protein, 0.3% lipids, 9% carbohydrates, and 3.8% fiber. Major sugars are sucrose (0.46 g/100 g), glucose (0.81 g/100 g), and fructose (0.93 g/100 g) (USDA 2006). Brussels sprouts are a rich source of vitamin C, containing on average 76–192 mg/100 g fresh weight and a moderate source of vitamin A (754 IU/100 g fresh weight), folate (61–208 μg/100 g fresh weight), carotenoids (1.090–1.160 mg/100 g fresh weight), β-carotene (140–1,020 μg/100 g fresh weight), lutein and zeaxanthin (920–2,710 μg/100 g fresh weight), and α-tocopherol (0.55–0.88 mg/100 g fresh weight) (Albrecht et al. 1990, 1991; Bushway et al. 1986; Kurilich et al. 1999; Malin 1977; Mullin et al. 1982; Noble 1967; Podsedek 2007; Podsedek et al. 2006; Singh et al. 2007; USDA 2006).

Brussels sprouts are also a good source of phenolic compounds (37.7–140.13 mg/100 g fresh weight), namely flavonoids (307 mg/100 g dry weight) and tannins (50 mg/100 g dry weight) (Heimler et al. 2006; Kaur and Kapoor 2002; Podsedek et al. 2006; Singh et al. 2007), which together with vitamin C are the major antioxidants of Brussels sprouts, due to their high content and antioxidant capacity (Cao et al. 1996; Podsedek 2007; Podsedek et al. 2006). Brussels sprouts contain glucosinolate compounds (10–601 μmol/100 g fresh weight), which have been considered as dietary protectors against cancer. Yet some of these compounds (i.e., sinigrin, progoitrin, and glucobrassicin) may confer a bitter taste to Brussels sprouts if present in high amounts (Carlson et al. 1987; Drewnowski and Gomez-Carneros 2000; Fenwick et al. 1983; Song and Thornalley 2007; Tian et al. 2005; van Doorn et al. 1998). The predominant glucosinolates detected in Brussels sprouts were sinigrin (1.3–4.9 g/kg fresh weight), gluconapin (6.9 μmol/g dry weight), glucobrassicin (3.2 μmol/g dry weight), and progoitrin (0.7–2.8 g/kg fresh weight) (Kushad et al. 1999; Song and Thornalley 2007; Tian et al. 2005; van Doorn et al. 1998). While Brussels sprouts with a sum of sinigrin and progoitrin below 2.2 g/kg fresh weight were appreciated by regular consumers, levels of sinigrin plus progoitrin below 0.6 g/kg fresh weight were appreciated as non-bitter and best accepted for consumers who dislike bitterness in Brussels sprouts (van Doorn 1999; van Doorn et al. 1998).

Optimum Postharvest Handling Conditions

Vacuum-cooling, hydro-cooling, forced-air cooling, or icing are effective methods to pre-cool Brussels sprouts, while packaging in vented bags will prevent excessive loss of moisture during handling. However, in order to reduce wilting during subsequent handling, Brussels sprouts should be wetted prior to vacuum-cooling (Stewart and Barger 1963). Following pre-cooling, Brussels sprouts should be kept at 0°C and 95–100% relative humidity. Under these conditions expected sprout life is about 3–5 weeks. Prolonged storage may result in black spotting of the leaves, loss of bright green color, yellowing, decay, and wilting. Storage at 5°C will reduce Brussels sprouts' postharvest life to 10–18 days, whereas storage at higher temperatures will result in accelerated deterioration. Yellowing and discoloration of the stem-end becomes evident within less than 7 days at 10°C (Anonymous 2004a; Cantwell and Suslow 2007a; Forney and Toivonen 2004a; Mills 2001; Ryall and Lipton 1979).

Brussels sprouts are very sensitive to exogenous ethylene. Exposure to ethylene will result in leaf yellowing and leaf abscission (Cantwell and Suslow 2007a; Forney and Toivonen 2004a).

Temperature Effects on Quality

Yellowing of the outer leaves was considered the major symptom of deterioration in Brussels sprouts, particularly when stored at temperatures above 0°C. When stored at low temperatures (0–5°C), loss of bright green color and discoloration of the cut-end developed after prolonged storage, and after 1 month the sprouts developed small dark lesions on the basal portion of the outer leaves. At higher temperatures (15–20°C), loss of quality was characterized by a rapid disappearance of chlorophyll from the outer leaves within a few days of storage, the cut-ends became discolored, and small roots developed near the outer margin of the cut surface in about 2 weeks. At 10°C, yellowing of the outer leaves was slower than at higher temperatures, but the cut-ends darkened at the same rate as those kept at higher temperatures (Lyons and Rappaport 1959). Brussels sprouts stored at 0°C maintained an excellent visual quality during 14 days of storage, but after 28 days, there was a significant deterioration in quality due to dehydration, browning of the stem-ends, decay, and yellowing (Viña et al. 2007).

Besides changes in the visual quality attributes of Brussels sprouts, other simultaneous changes in the compositional value of the sprouts also are dependent on temperature. Loss of moisture during storage not only contributes to deterioration in appearance due to wilting and yellowing but also leads to compositional deterioration due to cell wall breakdown and exposure of cell contents to oxidation. For example, in Brussels sprouts stored at 0°C weight loss reached more than 8% after 14 days, resulting in a dry appearance. After 42 days at 0°C, weight loss ranged from 22 to 33% (Viña et al. 2007). Storage for 3 weeks at 2°C or for 7 days under household refrigerated conditions (4–8°C) resulted in a 5 or 6% decrease, respectively, in the initial moisture content of Brussels sprouts (Albrecht et al. 1990; Song and Thornalley 2007), whereas when stored at ambient temperature (12–20°C), weight loss of Brussels sprouts increased to a maximum of 11.4% after 7 days. At this storage time, the sprouts appeared dehydrated (Song and Thornalley 2007). In fact, a maximum of 8% weight loss was considered to be the limit before Brussels sprouts became unacceptable for sale (Robinson et al. 1975). Use of plastic film packaging may help to reduce weight loss, browning of the cut surfaces, and yellowing of the leaves in Brussels sprouts stored at 0°C (Viña et al. 2007).

No significant reduction was observed in the initial ascorbic acid content of Brussels sprouts during storage for 42 days at 0°C (Viña et al. 2007). Similarly, initial ascorbic acid content of Brussels sprouts decreased by only 5% (from 118.83 to 113.08 mg/100 g fresh weight) after 3 weeks of storage at 2°C (Albrecht et al. 1990). However, when stored at 20°C, the initial ascorbic acid content of Brussels sprouts was decreased by about 36% (from 57.6 mg to 37 mg/100 g fresh weight) after only 4 days of storage (Wills et al. 1984). While total flavonoid content remained quite stable in Brussels sprouts stored at 0°C for 42 days (Viña et al. 2007), glucosinolate content of Brussels sprouts stored at 4–8°C decreased by 20% after 7 days of storage (Song and Thornalley 2007).

Time and Temperature Effects on the Visual Quality of 'Vancouver' Brussels Sprouts

'Vancouver' Brussels sprout buds shown in Figures 6.35–6.39 were harvested firm and compact from a commercial operation in the Orleans Island, Quebec, Canada, during the fall season (i.e., October). Promptly after harvest, fresh Brussels sprouts were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Loss of bright green color, yellowing of the outer leaves, darkening of the cut stem-end surface, and black spotting are the major changes that take place in the visual quality attributes during storage of 'Vancouver' Brussels sprouts. In general, yellowing and wilting of the outer leaves occurs faster at temperatures higher than 0°C and determines the maximum postharvest life of the sprouts. 'Vancouver' Brussels sprouts stored at 0°C maintain acceptable visual quality during 16 days of storage (Figure 6.35). After 16 days, the leaves turn from bright green to a yellowish-green with some edge browning also evident. The cut stem-end surface turns brown and dry, and after 26 days the outer leaves appear completely yellowish and dry, the stem-end cut surface appears brownish and dry, while some spots of brownish discoloration are also noticeable.

'Vancouver' Brussels sprouts maintain acceptable visual quality during storage for 15 days at 5°C (Figure 6.36). However, even if not visually perceptible, after 12 days the sprouts are somewhat softer than those stored at 0°C. After 15 days, the outer leaves become dull green, the edges are wilted and brownish, and the cut surface of the stem-end appears dry and slightly brownish, while first yellowing is perceptible. After 21 days, the outer leaves are yellowish and dry, and the cut stem-end surface is brownish and dry, while some spots of brownish discoloration are also noticeable.

Storage of 'Vancouver' Brussels sprouts at 10°C contributes to accelerated loss of bright green color, yellowing, and wilted appearance (Figure 6.37). The sprout maintains acceptable visual quality during 8 days, after which the outer leaves start to develop a yellowish coloration and appear less turgid and more wilted than at harvest. After 12 days, the external leaves are completely yellowish and wilted, while the cut stem-end surface appears dry and brownish. Besides the deterioration in appearance, at this time the sprouts feel soft and spongy when a slight finger pressure is applied.

Development of wilting in ‘Vancouver’ Brussels sprouts stored at 15°C appears to be faster than yellowing, as after only 4 days the outer leaves appear less turgid, more wilted, and less bright green than at harvest (Figure 6.38). Loss of bright green color and yellowing develops after 6 days, and after 8 days the outer leaves appear much wilted and the color becomes greenish-yellow. At this time, although not visually perceptible, the sprout feels very soft and spongy when squeezed.

‘Vancouver’ Brussels sprouts maintain acceptable visual quality during 3 days at 20°C (Figure 6.39). On day 4, some subtle lines of browning are noticeable on the outer leaves, while wilting of the outer leaves is also evident. Leaf wilting and brownish appearance increases as storage progresses, and after 8 days the outer leaves are severely wilted and yellowish-green, while some spots of brownish discoloration are also noticeable.

Overall, good visual quality of ‘Vancouver’ Brussels sprouts is maintained for longer periods of time when the sprouts are stored at 0 and 5°C (16 and 15 days, respectively), whereas storage at 10, 15, and 20°C reduced the postharvest life of the sprouts to 8, 4, and 3 days, respectively.

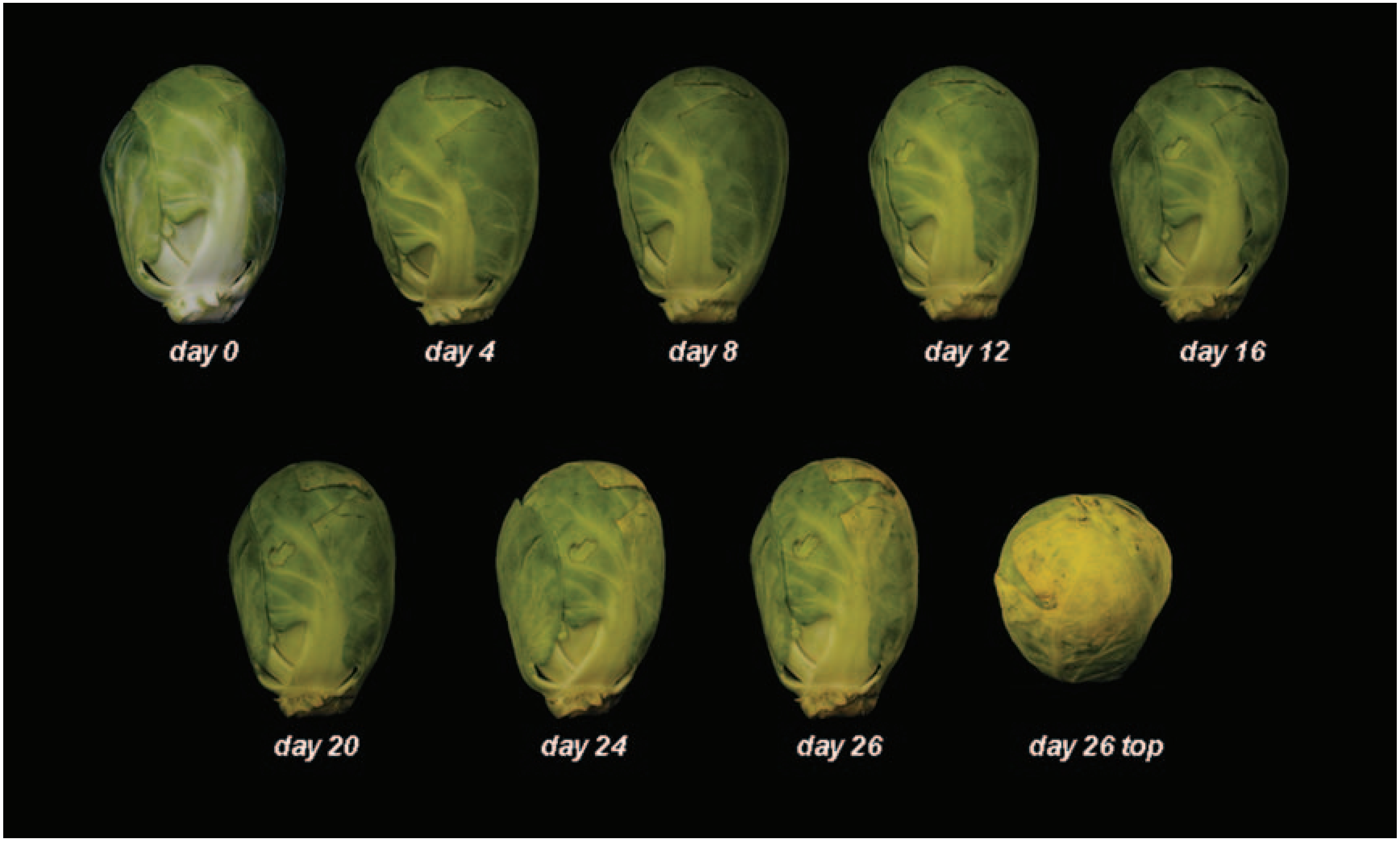
day 0
day 4
day 8
day 12
day 16
day 20
day 24
day 26
day 26 top

Figure 6.35. Appearance of 'Vancouver' Brussels sprouts stored for 26 days at 0°C. The sprout maintains acceptable visual quality during 16 days.

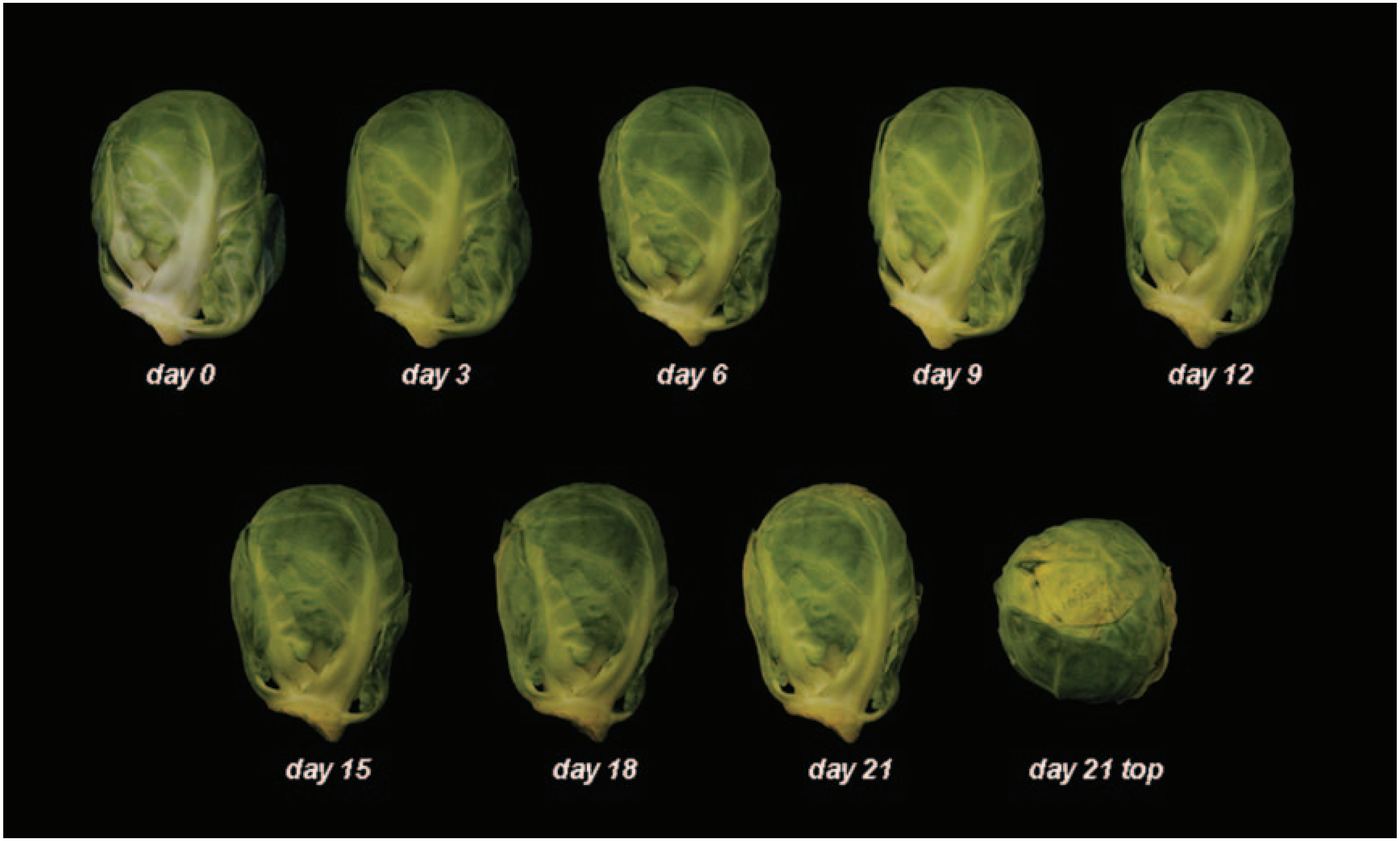
day 0
day 3
day 6
day 9
day 12
day 15
day 18
day 21
day 21 top

Figure 6.36. Appearance of ‘Vancouver’ Brussels sprouts stored for 21 days at 5°C. The sprout maintains acceptable visual quality during 15 days.

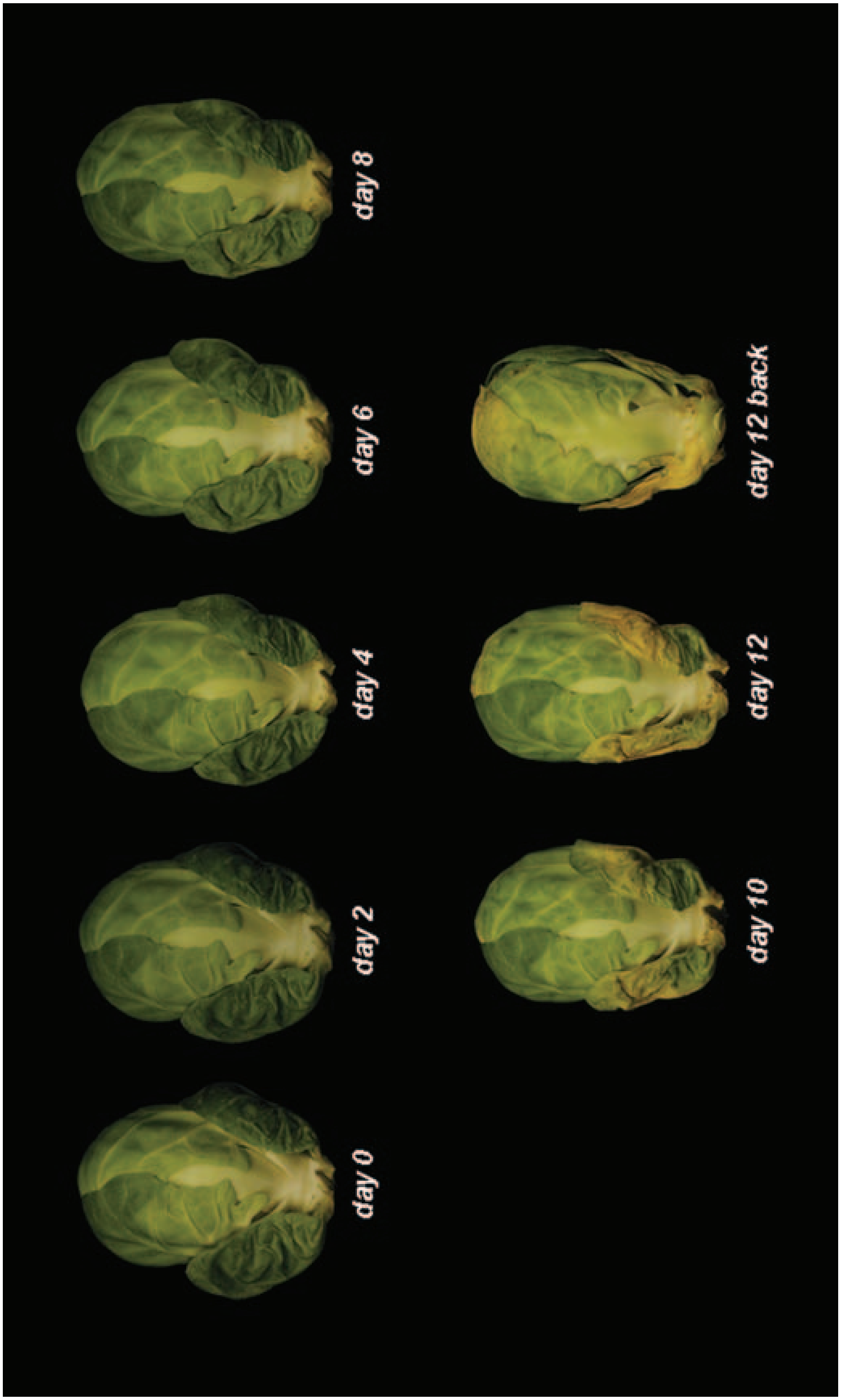
day 0
day 2
day 4
day 6
day 8
day 10
day 12
day 12 back

Figure 6.37. Appearance of 'Vancouver' Brussels sprouts stored for 12 days at 10°C. The sprout maintains acceptable visual quality during 8 days.

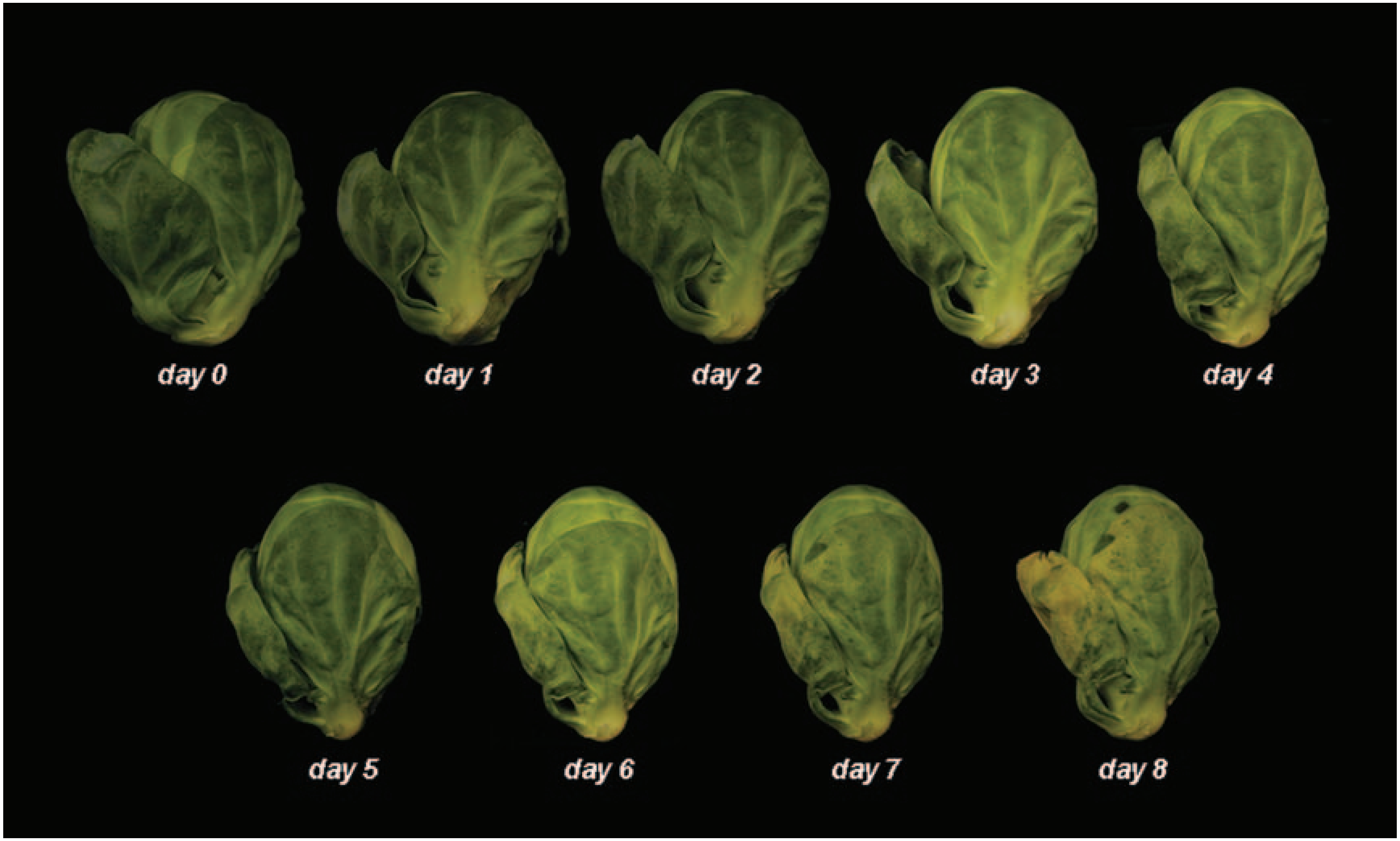
day 0
day 1
day 2
day 3
day 4
day 5
day 6
day 7
day 8

Figure 6.38. Appearance of 'Vancouver' Brussels sprouts stored for 8 days at 15°C. The sprout maintains acceptable visual quality during 4 days.

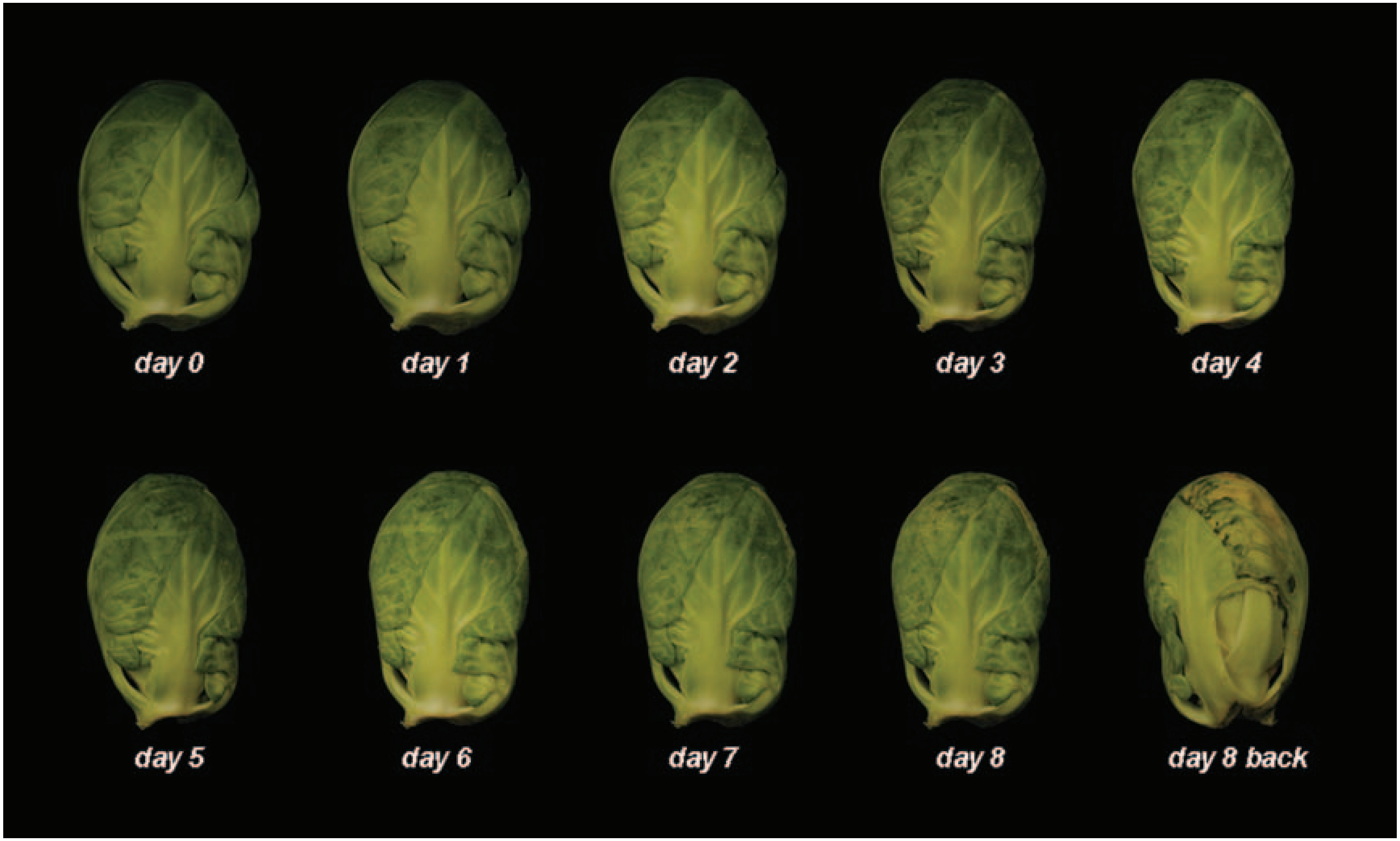
day 0
day 1
day 2
day 3
day 4
day 5
day 6
day 7
day 8
day 8 back

Figure 6.39. Appearance of ‘Vancouver’ Brussels sprouts stored for 8 days at 20°C. The sprout maintains acceptable visual quality during 3 days.

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CHAPTER 7

STEM, LEAF, AND OTHER VEGETABLES

Asparagus
Lettuce
Witloof Chicory
Mushroom
Bibliography

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ASPARAGUS

Scientific Name: *Asparagus officinalis* L.
Family: Liliaceae

Quality Characteristics

Texture and fiber content are two of the most important quality attributes, as they affect the eating quality of asparagus spears (Huyskens-Keil et al. 2005; Jaramillo et al. 2007; Sosa-Coronel et al. 1976). High-quality asparagus should be firm but not tough and have a uniform dark green or white color with tightly closed and compact tips. Stems should be straight, tender, and glossy in appearance. Tip desiccation is associated with poor quality (Lipton 1990; Luo et al. 2004). Furthermore, good quality asparagus should have a pleasant and bitter-free taste (Fehér 1994a). Green asparagus is in general preferred over the white asparagus spears, as the latter are associated with increased toughness (Brovelli et al. 1998; Papadopoulou et al. 2002; Rodríguez et al. 2004). Besides cultivar variations, asparagus quality characteristics were reported to change during the season of harvest. Thus, asparagus from late season (October) was tougher and had lower sugar and acid content than that from early season (March through August). As the season progressed, spears lost 0.2–1.3 weeks of postharvest life from an initial duration of 2.7 weeks (Bhowmik et al. 2002). Spears harvested during cool weather were found to have nearly twice as much tougher skin than those harvested during warm periods (Poll 1996; Zurera et al. 2000). Increase in asparagus fibrousness during the season of harvest was attributed to slow growth due to cold weather and also to enhanced ethylene production caused by a wounding reaction when the spears are cut. This wounding reaction leads to increased lignification in the lower part of the spear, resulting in a tougher asparagus (Bhowmik et al. 2002; Brovelli et al. 1998; Lipton 1990). In fact, basal spear sections showed the highest proportion of fiber, followed by the middle and tip portions (Brovelli et al. 1988; Sosa-Coronel et al. 1976; Zurera et al. 2000). Furthermore, compared to thinner asparagus, thicker spears were reported to have considerably thicker cell walls, higher content of dietary fiber, and consequently increased fibrousness (Zurera et al. 2000). A dietary fiber content of 0.25% was reported to be the critical level above which the consumers start to notice asparagus fibrousness (Poll 1996). As the season advances, the average daily temperatures increase, and consequently the asparagus growth rate increases. Accelerated spear growth results in a decrease in soluble solids content owing to a decline in the amount of carbohydrates in the tips (Bhowmik et al. 2002).

Overall, asparagus contains approximately 92% water, 4.5% carbohydrates, 0.9% proteins and 2.1% fiber, 13 mg of vitamin C, 128 μg folate, and 583 IU of vitamin A per 100 g of fresh weight, as well as other vitamins in minor concentrations (Marlett and Vollendorf 1993; USDA 2006). Although white asparagus is in general more expensive than green asparagus, the latter is in general less fibrous and has a higher nutritional value (Brovelli et al. 1998; Fehér 1994a; Rodríguez et al. 2004, 2005). White asparagus has significantly less protein, lower ascorbic acid and phenolic content, and higher acidity and soluble solids content than green asparagus. Asparagus chemical composition varies depending on the season of harvest, the height, and the section of the spear. For example, ascorbic acid content of freshly harvested asparagus decreased from March until July, and spears harvested in May, June, and July had significantly lower ascorbic acid content than asparagus harvested in March and April (Esteve et al. 1995). In addition, the highest concentration of soluble solids was observed in the middle segment of the spear, while the tip had the lowest concentration. On the other hand, proteins, minerals, and ascorbic acid levels were higher in the upper segments of the spear, decreasing gradually to the base segment (Amaro-López et al. 1999; Lill et al. 1990; Makus and Gonzalez 1991). Finally, tips of taller asparagus had lower sugar and higher malic acid contents and more protein than tips of shorter spears (Lill et al. 1990).

Optimum Postharvest Handling Conditions

Fresh asparagus deteriorates very quickly following harvest, becoming unacceptable for sale after about 5 days at 20°C due to physiological changes such as toughening, flavor changes, and losses in chlorophyll, ascorbic acid, and carbohydrates (King et al. 1993). In order to retard quality losses and extend postharvest life to about 2 or 3 weeks, asparagus should be promptly pre-cooled after harvest to a temperature between 0 and 2°C. Pre-cooling asparagus to 2°C prior to storage at 1.5°C reduced total quality losses by 20–30% (Gariépy et al. 1991). In order to maintain a fresh appearance and reduce tip rot and moisture loss during subsequent storage, asparagus should be hydro-cooled or forced-air cooled within 4–12 hours after harvest (Lallu et al. 2000). Textural changes in asparagus during storage are also greatly dependent on temperature and delay before pre-cooling. For example, a 4-hour delay before pre-cooling was reported to result in about a 40% increase in resistance to shear force due to toughening of the tissues (Hernández-Rivera et al. 1992). Hydro-cooled spears lost less weight (4%) than forced-air or passively cooled (8%) spears after either 3 days or 3 weeks of storage at 2°C (Lallu et al. 2000). During short-term storage, hydro-cooled asparagus was less tough, had lower incidence of tip rot, and had a better visual quality than forced-air or passively cooled spears (Lallu et al. 2000). Forced-air cooling of asparagus to 1°C after exposure to 20°C for 5 hours extended the postharvest life of the spears for at least 7 days, by reducing the loss of moisture and maintaining a better texture, compared to room-cooled asparagus at 1 or 10°C (Laurin et al. 2003). Asparagus suffering from temperature abuse during shipping should be immediately forced-air cooled to 1°C in order to delay further deterioration (Laurin et al. 2003). Use of insulated pallet covers combined with adequate cooling can be used to avoid overheating of pallets during air shipment of asparagus (Bycroft et al. 1996). High relative humidity (95–100%) during storage is essential to prevent desiccation and loss of glossiness of the asparagus spears (Luo et al. 2004). Although temperatures between 0 and 2°C are recommended for storage of asparagus, prolonged exposure to temperatures lower than 2°C may eventually result in chilling injury (CI). Asparagus is subject to CI after about 10 days at 0°C, and symptoms include loss of sheen and glossiness and graying of tips. A limp, wilted appearance may also be observed. Severe chilling may result in darkened spots or streaks near the tips (Luo et al. 2004).

Temperature Effects on Quality

When exposed to adverse environmental conditions asparagus spears lose their visual and eating quality very quickly after harvest. The main factor that limits the postharvest life of asparagus is tip breakdown. In fact, tips are usually the first part of the spear to show symptoms of deterioration such as feathering and browning of bracts, tissue darkening and flaccidity, cellular breakdown, and physiological decline. Although the lower sections of the spears are less affected, tips of spears soften, become flaccid, and darken, becoming less glossy, and develop a dull gray-green or deep purple color (Lipton 1990).

Color changes in white asparagus during storage are associated with development of an intense purple color in the spear tip due to anthocyanin synthesis, which increases with increasing storage temperature. Increase in anthocyanin content was associated with an increase in a* value and a decrease in hue (Papadopoulou et al. 2002). In green asparagus, changes in color during storage are mostly associated with a decrease in total chlorophyll (Papadopoulou et al. 2002). Asparagus brightness (L* value) also decreases during storage, regardless of the temperature. After storage most of the spears were darker and less bright than at the time of harvest, mostly due to development of brownish or purplish-green color. Decrease in L* value may also reflect loss of glossiness as a result of loss of moisture during storage. Chroma of the asparagus slightly decreased, meaning that the spears were less vivid after storage than at the time of harvest (Nunes and Emond 2002a).

During storage asparagus tends to become less turgid and tougher, and temperature greatly influences such textural changes. Compared to storage at 4°C, asparagus stored at 20°C for 1 day showed a rapid increase in cell wall thickness and consequently increased toughness (Zurera et al. 2000). Likewise, storage for 3 days at 21°C significantly increased asparagus strength, mainly in the last portion of the stem (Rodriguez-Arcos et al. 2002b).

Textural changes during postharvest life of asparagus are also markedly affected by the tissue water status. Cell expansion was shown to continue even without any water supply, particularly in the first 24 hours at 20°C, due to internal reallocation of water from other parts of the spear (Heyes et al. 1998).

Although firmness of asparagus to the touch tends to decrease during storage, it is well known that the fiber content of the asparagus increases during storage, particularly at high temperatures, and the spears become more tough and hard to cook. However, lignification proceeds more slowly near the tip than in the middle or near the base of the stalks (Lipton 1990). Lignin content increases during storage, contributing to a tougher texture, while loss of moisture results in a less turgid spear (Everson et al. 1992; Liu and Jiang 2006). For example, in asparagus stored at 2°C the shear force increased by 70.2% after 14 days of storage (Villannueva et al. 2005). Likewise, in asparagus stored for 1 day at 1°C and then transferred to 20°C for 6 days, shear forces needed to cut stems increased, and the initial lignin content increased by more than 400% (Everson et al. 1992). Storage of asparagus at ambient temperature resulted in a 180% increase in lignin content compared to initial values (Liu and Jiang 2006). Holding asparagus for 3 days at ambient temperature resulted in increased strength and toughness, and the increase was much greater in white than in green asparagus (Rodríguez et al. 2004). Asparagus elasticity decreased during storage at 0 or 20°C and remained constant at 5 or 10°C, while tissue strength decreased at all temperatures. Changes in asparagus elasticity and tissue strength were associated with the water status of the spear and its loss or turgor (Huyskens-Keil et al. 2005).

In green asparagus ‘Guelph Millennium,’ firmness to the touch decreased during storage, regardless of the storage temperature. After storage the spears were less turgid and less straight and bent easily. Asparagus stored at 15 or 20°C lost its firmness faster than that stored at lower temperatures, and after approximately 2–3 days it was considered unmarketable (Nunes and Emond 2002a). Hernández-Rivera et al. (1992) also reported that textural changes in asparagus are extremely responsive to temperature. The tip of the asparagus

gus spear was the first to show symptoms of loss of firmness, probably because of its greater fragility compared to the body of the spear. Some of the tips became very soft and slimy after storage, particularly those stored at temperatures higher than 5°C (Nunes and Emond 2002a). In asparagus stored at 20°C, bracts lost their turgidity within 48 hours while auxiliary buds and central meristem retained turgidity for over 96 hours (Heyes et al. 1998). After 1 week at 1.5°C, breaking force increased, meaning that the asparagus was tougher than at harvest, and toughness of the spears was greater in the bottom portion than in the top (Bhowmik et al. 2002).

White asparagus is considered more fibrous than green asparagus, and after storage for 6 days at 1 or 10°C textural changes are more accentuated and faster in white asparagus, resulting in a tougher spear compared to green asparagus (Papadopoulou et al. 2002).

Feathering of the asparagus tips is a sign of senescence and indicates that the spear was exposed to unfavorable temperatures after harvest. Postharvest feathering is also aggravated when asparagus is exposed to low relative humidity (Ryall and Lipton 1979). For example, asparagus stored at temperatures higher than 15°C showed feathering of spears (Siomos et al. 1995c).

Postharvest temperature also influences the growth and geotropic curvature of asparagus spears (King et al. 1993; Luo et al. 2004; Rodriguez-Arcos et al. 2002a), and the shape of the spears may change during storage from straight to curved, as seen in asparagus stored at temperatures higher than 5°C (Nunes and Emond 2002a). If stored at temperatures above 5°C, asparagus continues to grow during the postharvest period (Luo et al. 2004). For example, length of asparagus stored for 3 days at 21°C increased in average by 0.5 cm, mainly in the upper stem section (Rodriguez-Arcos et al. 2002a). Curvature and length of green asparagus spears significantly increased with an increase in the storage temperature from 2 to 22°C (Paull and Chen 1999).

Geotropic curvature of asparagus after harvest may be prevented using a brief hot-water treatment at 47.5°C for 2–5 minutes, followed by prompt cooling, without compromising the overall appearance and quality of the spears (Paull and Chen 1999). White asparagus pretreated with hot water at 55°C for 2–3 minutes showed significantly lower anthocyanin content and less violet color development after subsequent storage, compared to nontreated spears (Siomos et al. 2005).

Perkins-Veazie et al. (1993) observed symptoms of CI in asparagus, expressed as loss of sheen and glossiness, flaccidity, and darkening of the tips to a gray-green color after 12 days of storage at 0°C. Some of the spears were also very limp and wilted, which was most likely due to CI rather than to water loss (Luo et al. 2004). After 14 days, approximately 30% of the spears stored at 0°C showed moderate signs of CI (Nunes and Emond 2002a).

Asparagus stored for 2 weeks at 0°C developed a slimy appearance after transfer to ambient temperature, most likely due to accelerated bacterial growth (Nunes and Emond 2002a). Otherwise, decay development was not a serious problem in asparagus, as it did not increase above objectionable levels. Asparagus stored at 5 or 10°C did not show any decay after 14 days in storage. However, some of the asparagus stored at 15 and 20°C showed a slimy appearance, most likely due to the growth of bacteria, which often results in soft rot. After 6 and 8 days at 15°C, 9 and 11% of the asparagus, respectively, showed slight symptoms of decay. Decay incidence increased with increasing the storage temperature, and after 4 days at 20°C, 7% of the asparagus showed signs of decay, which increased to 64% after 8 days (Nunes and Emond 2002a). It was previously reported that after 13 days at 12°C asparagus spears were completely spoiled (Garcia-Gimeno et al. 1998). Slimy spears also released an unpleasant aroma compared to good quality spears. After storage, asparagus developed an unpleasant musty rot-like aroma that rendered the spears unacceptable for sale. Although aroma of asparagus changes during storage regardless of the temperature, aroma of spears stored at 20°C was very unpleasant after only 2 days of storage (Nunes and Emond 2002a). It was previously reported that after 6 days at 20°C asparagus spears were completely spoiled (Garcia-Gimeno et al. 1998), while after 9–12 days at 2°C asparagus showed longitudinal striation, dryness toward the base, loss of firmness, feathering (bract opening) and changes in color from a bright green to a dull olive green (Villannueva et al. 2005). Others have reported a maximum postharvest life of 19 days for green asparagus stored at 2°C and 95% humidity (Casas and Nuñez 2002).

Besides maintaining an optimum temperature during storage, it is very important to maintain the moisture content of fresh asparagus by increasing the humidity around the spears. Moisture content greatly affects spear appearance, tenderness, and postharvest life. Asparagus spears can lose about 2% of their initial weight in 24 hours if held at temperatures between 20 and 22°C and 65–70% relative humidity (Fehér 1994b). When held for 24 hours at temperatures between 1 and 3°C and 80–85% relative humidity, asparagus spears may lose about 1% of their weight, and after 2–3 days under the same conditions weight loss may reach 3% (Fehér 1994b). During handling and packing at the grower, white asparagus was reported to lose between approximately 1.4 and 2% of its initial weight after 48 and 74 hours, respectively, when the average temperatures were 16°C before pre-cooling and 1–2°C after pre-cooling (Siomos et al. 1995a, 1995b).

As the temperature increases, weight loss increases due to larger water vapor pressure deficits between the air and tissue. For example, after 6 days at 2.5, 15, or 25°C, weight losses of 0.8, 1.9, and 4% were observed in freshly harvested white asparagus (Siomos et al. 1995c). In green asparagus stored at 1 or 10°C weight losses were approximately 6 and 7%, respectively (Papadopoulou et al. 2002). Other studies have shown that weight loss of non-packed asparagus stored at 1 and 5°C may be as high as 22.9 and 18.7%, respectively, after 30 days of storage, while at 10 and 20°C weight loss may reach 11.9 and 18.1%, respectively, after only 3 days of storage (Itoh 1986).

Furthermore, weight loss and, consequently, loss of freshness seem to be more rapid and significantly higher in the tip of the spear than at the bottom (Fehér 1994b). Other studies, however, reported that weight loss in asparagus stored for 3 days at 21°C occurred mainly in the lower and basal sections, which lost 7.7 and 14.8% of their weights, respectively, compared to lower weight losses in the top (4.2%) and middle sections (3.1%) (Rodriguez-Arcos et al. 2002a). Nevertheless, even if the lower parts of the spears seem to lose more water during storage due to their more delicate structure, the tip of the spear shows in general signs of loss of moisture before the other parts of the spear.

Weight loss in 'Guelph Millennium' asparagus increased during storage, regardless of the storage temperature (Nunes and Emond 2002a). However, the amount of weight loss increased with increasing storage temperature. Thus, after approximately 4–5 days spears stored at 20°C attained 8% weight loss, which is the maximum acceptable level before asparagus is considered unmarketable, according to Robinson et al. (1975). Asparagus stored at 0°C attained the maximum acceptable weight loss after approximately 13 days of storage. However, signs of wilting in asparagus stored at 0°C were noticeable after 8–9 days of storage, which corresponded to approximately 4–5% weight loss (Nunes and Emond 2002a). Storage of asparagus for 14 days at 2°C resulted in an 11.8% reduction of its initial weight (Villannueva et al. 2005). For asparagus stored at 5°C, weight loss attained the maximum acceptable level after approximately 9–12 days, while wilting was already objectionable after 6–8 days. At that time, asparagus stored at 5°C had lost approximately 6–7% of its weight (Nunes and Emond 2002a). Although Krarup (1990) suggested that the 8% maximum permissible loss of fresh weight proposed by Robinson et al. (1975) is too low, results from the present study suggest the opposite; that is, that symptoms related to loss of moisture such as loss of firmness and wilting may appear before weight loss reaches 8%. Therefore, values of weight loss between 4 and 8% should be considered as the maximum permissible before 'Guelph Millenium' asparagus is considered unacceptable for sale (Nunes and Emond 2002a).

Asparagus wilts quite quickly during storage, particularly when stored at high temperatures. Wilting was relatively fast even at 0°C, most likely due to chilling damage caused to the spears stored at this temperature. After 8 days at 0°C the spears already showed moderate signs of wilting. For asparagus stored at 20°C, the earliest symptoms of water loss included feathering of the bracts (Heyes et al. 2001). After approximately 3 days at 20°C, 'Guelph Millennium' spears had attained an objectionable wilting rate, and after approximately 6 days the bracts started to show some browning (Nunes and Emond 2002a). It has been reported that water loss from the asparagus tissues is not uniform. In fact, during the first 24 hours after harvest in spears held at 20°C, 35% of the water is lost from the tip (with crowded bracts), 40% from the cut-end, and the remainder from the rest of the spear surface. Detailed examination also showed that shrinkage of the outer cell layers of asparagus was not paralleled by shrinkage of the internal tissues, suggesting that the water lost from the stem surface was not replaced from deeper regions (Heyes et al. 2001).

Storage temperature also has a great impact on asparagus composition and, concurrently with changes in appearance, texture, and moisture content, changes in sugars, acids, pigments, and vitamins also occur. Soluble solids content declined considerably during the first 24 hours after harvest in asparagus stored at 16°C. This decline was greater in the upper parts of the spear than in the basal part, and glucose was more affected than fructose (Lill et al. 1990). Soluble solids content of asparagus stored for 6 days at temperatures between 2.5 and 25°C decreased, regardless of the temperature. However, at 25°C the decrease in soluble solids content was more than five times higher than that at 2.5°C (Siomos et al. 1995c). The sugar content of asparagus gradually decreased during 7 days of storage at 1.5°C, and the decrease was slightly higher in the top portion of the spears than in the bottom part (Bhowmik et al. 2002).

Malic and citric acid concentrations in asparagus stored at 16°C remained constant for 24 hours after harvest, but doubled in the tip of the spears after 72 hours (Lill et al. 1990). Likewise, asparagus acidity increased after 6 days of storage at 1 or 10°C; however, the increase was significantly higher at 10°C. On the other hand, pH of the spears decreased during storage (Papadopoulou et al. 2002). Storage of asparagus spears for 14 days at 2°C resulted in approximately 4–18% decrease in pH and 20–57% increase in acidity (Villannueva et al. 2005).

Protein content of asparagus stored at 16°C did not change after the first day, but after 3 days at the same temperature it declined significantly in the tip of the spear (Lill et al. 1990). Ascorbic acid content of asparagus also decreased, regardless of the storage temperature. Initial ascorbic acid content of asparagus stored at 2.5°C was reduced by about 50% after 6 days, while in asparagus stored at 25°C losses were as high as 80% (Siomos et al. 1995c). Likewise, ascorbic acid content of asparagus stored at 2°C significantly decreased during storage, resulting in retention of 40.3–28.1% after 14 and 16 days of storage, respectively (Villannueva et al. 2005). In another study, the initial ascorbic acid content of asparagus was reduced by approximately 74% (from 52.8 to 13.59 mg/100 g fresh weight) after 3 weeks of storage at 4°C (Albrecht et al. 1991). Furthermore, it seems that exposure of asparagus to light during storage at 2.5 or 5°C contributed to further losses in ascorbic acid compared to dark-stored asparagus (Siomos et al. 1995c). Although ascorbic acid content of white and green asparagus decreased during storage at 1 or 10°C, white asparagus better retained its initial ascorbic acid content (80 and 77% retention, respectively) compared to green asparagus (71 and 41% retention, respectively) (Papadopoulou et al. 2002).

After storage for 6 days at 1 or 10°C the total soluble phenol content decreased in white or green asparagus

(Papadopoulou et al. 2002). For green asparagus stored at ambient temperature total phenol concentration increased sharply after 3 days but declined afterward from 1,729 to 1,364 µg/g of fresh asparagus (Liu and Jiang 2006). For white asparagus stored at ambient temperature the amount of phenolic content doubled after storage compared to freshly harvested asparagus (Jaramillo et al. 2007). Increases in phenolic content were observed during storage at 21°C for 3 days, particularly in the middle and lower section of asparagus spears (Rodríguez et al. 2005; Rodriguez-Arcos et al. 2002a). Accumulation of phenolic content and ferulic acid, particularly during storage of white asparagus, has been correlated with changes in texture and increased toughening of the spears (Jaramillo et al. 2007).

Anthocyanin synthesis also increases with increasing storage temperature, and the synthesis of the pigment further increased when asparagus was held under light conditions compared to dark storage. Thus, light-stored spears at 20 and 25°C had higher anthocyanin content than asparagus stored in the dark (Siomos et al. 1995c). Increase in anthocyanin content during storage causes the development of a purplish color and is considered a sign of poor quality, particularly in white asparagus (Papadopoulou et al. 2002).

Total carotenoid content of green asparagus decreased during a 14-day storage period at 2°C, and after 14 days the losses for β-carotene ranged from 53.5 to 61.3%. Total chlorophyll content also decreased during storage of green asparagus at 2°C. After 16 days at 2°C losses of chlorophyll "b" in green asparagus were approximately 38 to 58% compared to the initial content at harvest. Losses in chlorophyll "a" also showed a sharp decline during storage, and after 16 days at 2°C a reduction of approximately 60% was observed (Tenorio et al. 2004). However, chlorophyll synthesis in asparagus stored at temperatures higher than 15°C may also occur, particularly if stored under light (Siomos et al. 1995c).

Time and Temperature Effects on the Visual Quality of 'Guelph Millennium' Asparagus

'Guelph Millennium' asparagus shown in Figures 7.1–7.5 was harvested dark green with tightly closed compact tips and straight, tender, firm, and glossy stalks, with an average length of 20 cm and an average diameter of 1.3 cm, from a commercial operation in Saint-Côme, Quebec, Canada, during the spring season (i.e., May). Promptly after harvest, fresh asparagus were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C and 20.0 ± 0.2°C) and with 95–98% relative humidity.

'Guelph Millennium' asparagus stored at 0°C maintains an acceptable visual quality up to 8 days in storage. After that time, the spear develops an objectionable color, wilting, and dryness of the bracts, which reduces the postharvest life of the spear due to poor visual quality. Symptoms of CI also develop after 8 days, the color of the spears becomes dull and grayish-green, and signs of feathering (expansion and opening of the tips, tips no longer compact and with loose bracts) are also evident. Curving of the tips was also evident at this temperature (Figure 7.1).

After 6–8 days at 5°C the spears were considered unacceptable for sale, as they developed an objectionable dull brownish-green color, wilting, and feathering of the bracts. After 12–14 days of storage the body of the spear shows moderate to severe wilting. Curving of the tips was also evident at this temperature (Figure 7.2).

Wilting is also an important quality factor for asparagus stored at 10°C, as it limits the postharvest life of the spears to approximately 4–6 days. After 6 days the spears are considered unacceptable for sale, as they develop an objectionable dull brownish-green color, limp and wilted appearance, feathering of the bracts, and curving of the tips. After 8 days the bracts develop a slimy appearance (Figure 7.3).

Asparagus stored at 15°C maintained an acceptable visual quality for up to 2–4 days of storage. After that period the spears were considered unacceptable for sale, as they developed an objectionable dull brownish-green color and were limp and wilted. Feathering of the bracts and curving of the tips are also evident at this temperature (Figure 7.4).

Asparagus stored at 20°C maintains an acceptable visual quality up to 2 days of storage. After 2 days the spears appear dry and dull in color and show slight feathering of the bracts. After 4 days the tips of the asparagus develop a brownish color, and after 6 days they appear completely brown, dry, and wilted. Curving of the tips was also evident at this temperature (Figure 7.5).

Overall, in 'Guelph Millennium' asparagus changes in color, wilting, feathering of the bracts, and tip curvature are the most important visual quality factors that limit the postharvest life of the asparagus. Increasing the storage time and temperature results in accelerated loss of quality. 'Guelph Millennium' asparagus stored at 0 and 5°C maintained a good quality for longer periods of time than asparagus stored at higher temperatures. However, after 8 days at 0°C, CI develops and deteriorates the visual quality of the spear. 'Guelph Millennium' asparagus visual quality remains acceptable during 6, 3, and 2 days when stored at 10, 15, and 20°C, respectively, but the spear deteriorates very quickly if storage is prolonged.

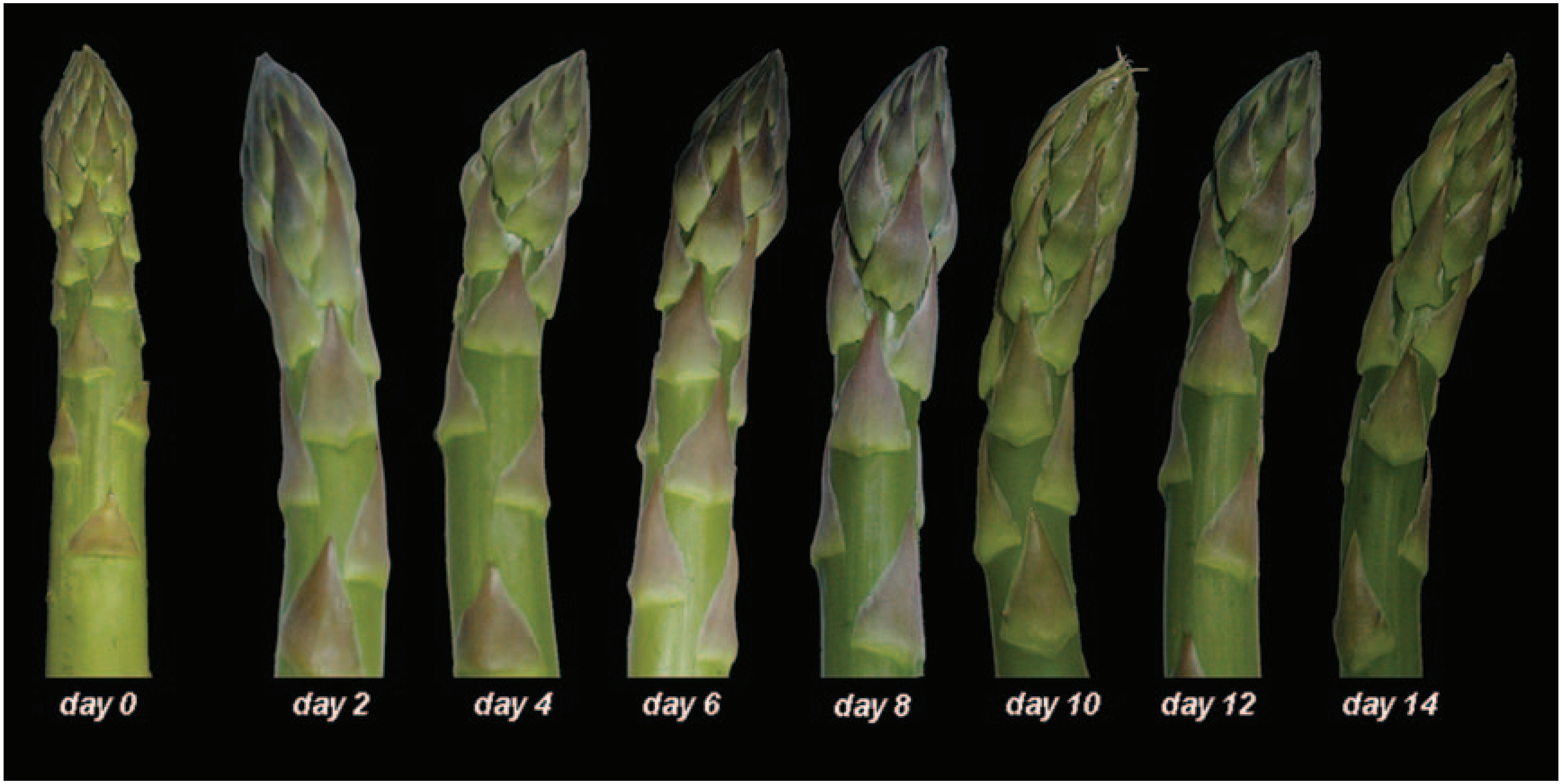

Figure 7.1. Appearance of asparagus 'Guelph Millennium' stored for 14 days at 0°C. Asparagus spears maintain an acceptable visual quality during 8 days. After 8 days, minor signs of CI become visible, and after 14 days the spears show moderate signs of CI such as graying of the tips, loss of glossiness, and flaccid appearance.

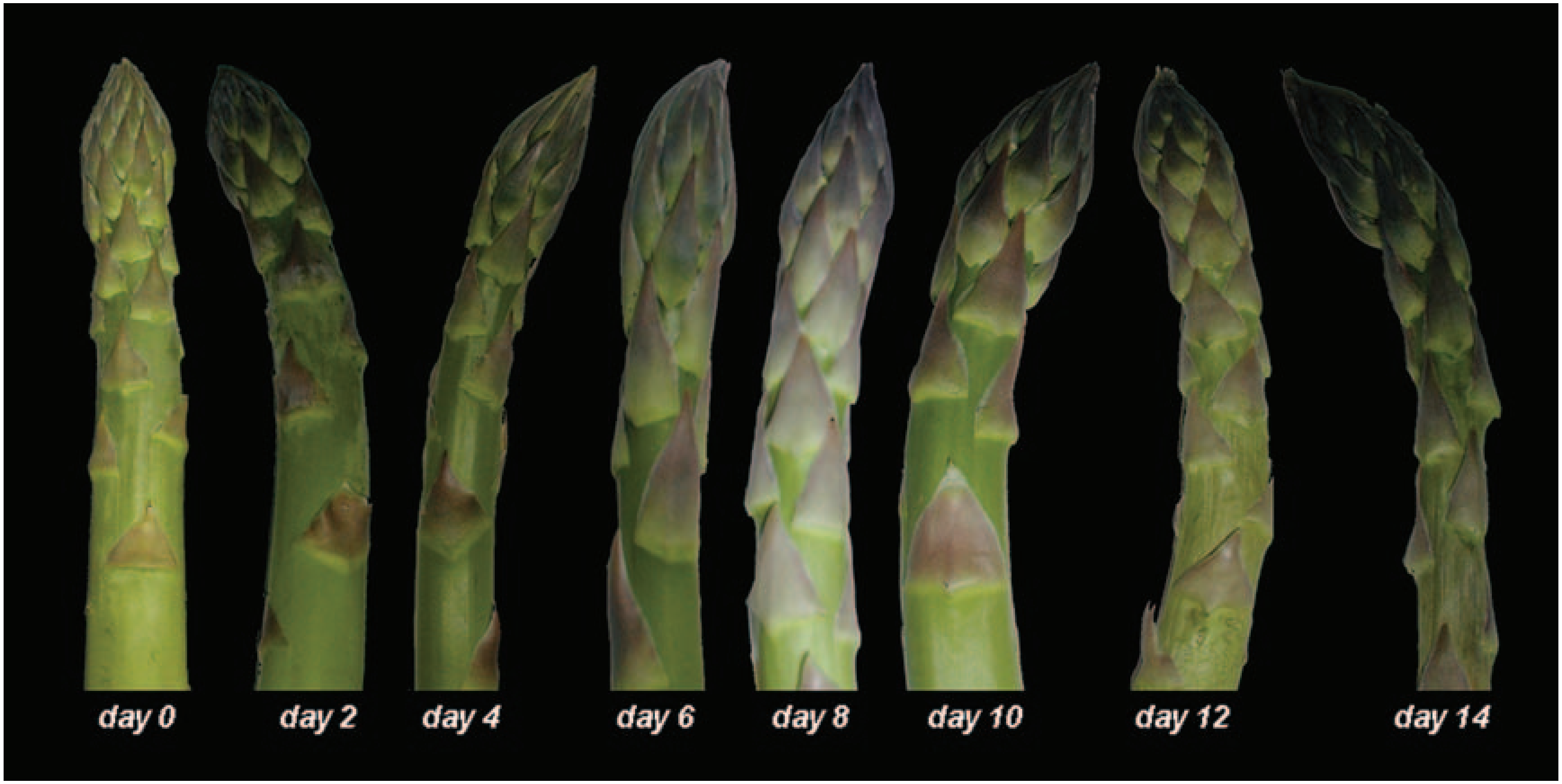
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Figure 7.2. Appearance of asparagus 'Guelph Millennium' stored for 14 days at 5°C. After 6–8 days spears develop a dull brownish-green color, signs of wilting, and feathering. Curving of the tips is also evident at this temperature.

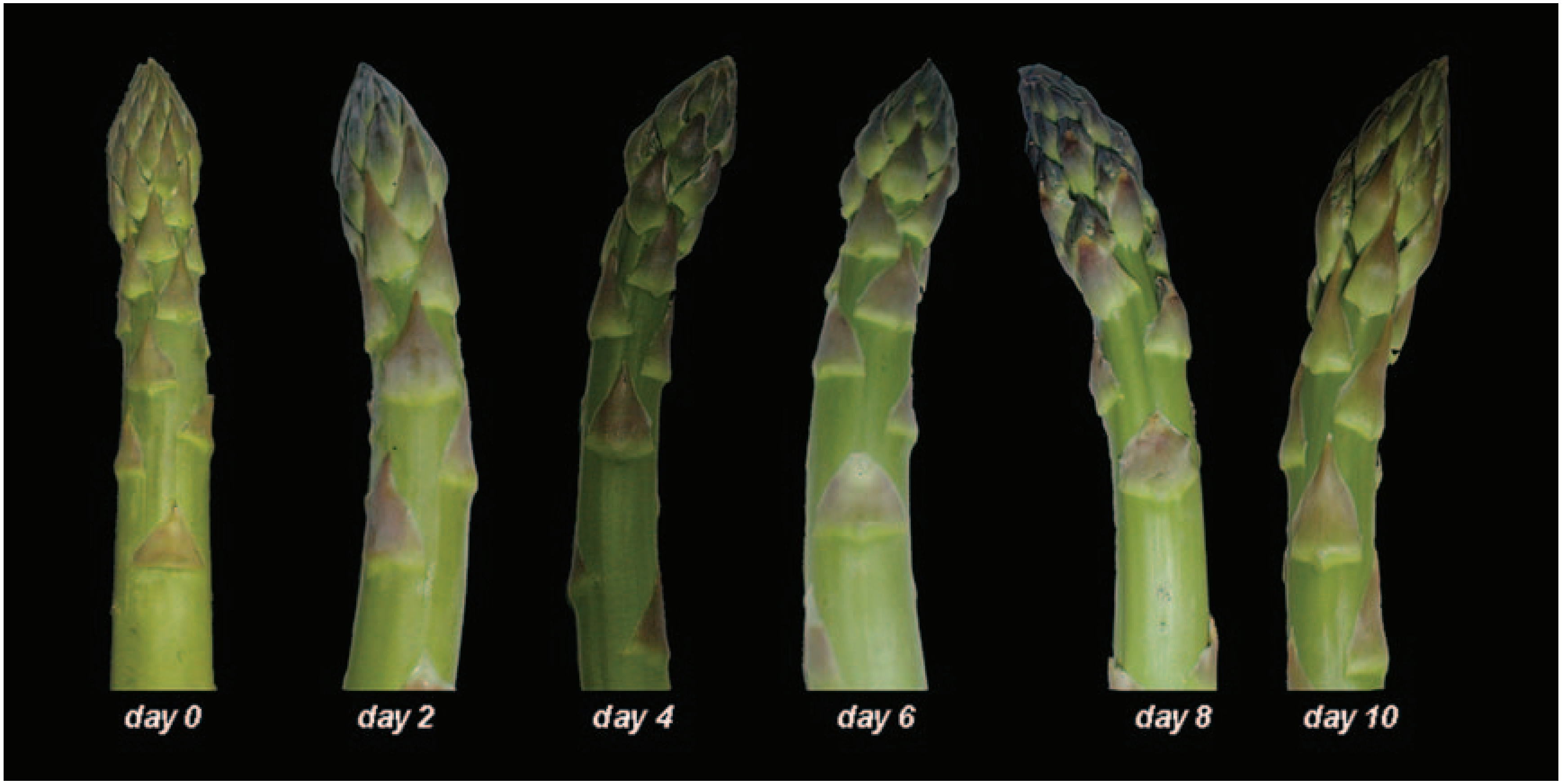

Figure 7.3. Appearance of asparagus ‘Guelph Millennium’ stored for 10 days at 10°C. After 6 days, spears develop a dull grayish-green color, loss of firmness of the tips, signs of wilting and dryness, feathering, and curving of the tips.

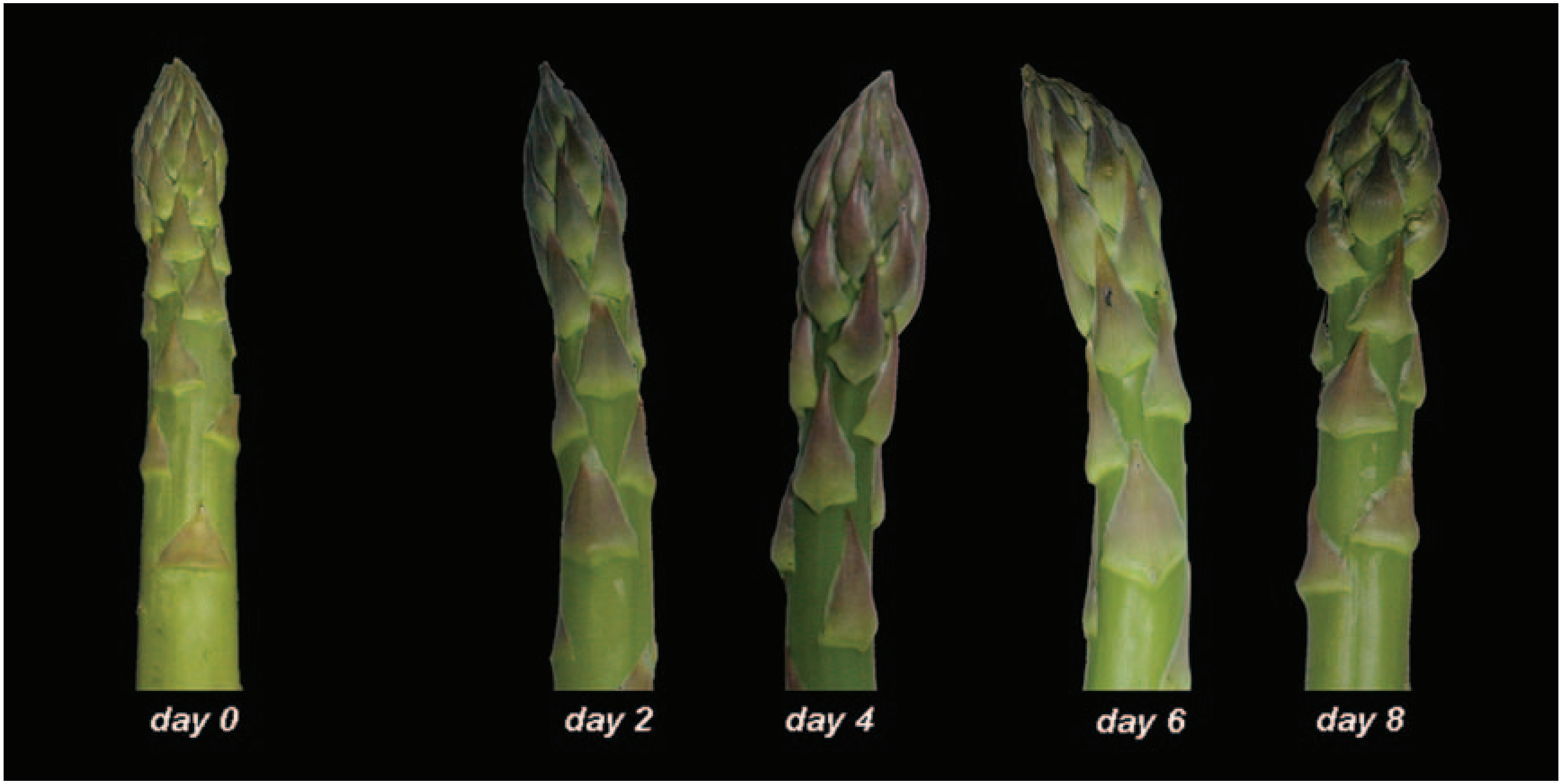

Figure 7.4. Appearance of asparagus ‘Guelph Millennium’ stored for 8 days at 15°C. After 4 days spears develop a dull grayish-green color, lose their firmness, and show signs of wilting and dryness, feathering, and curving of the tips.

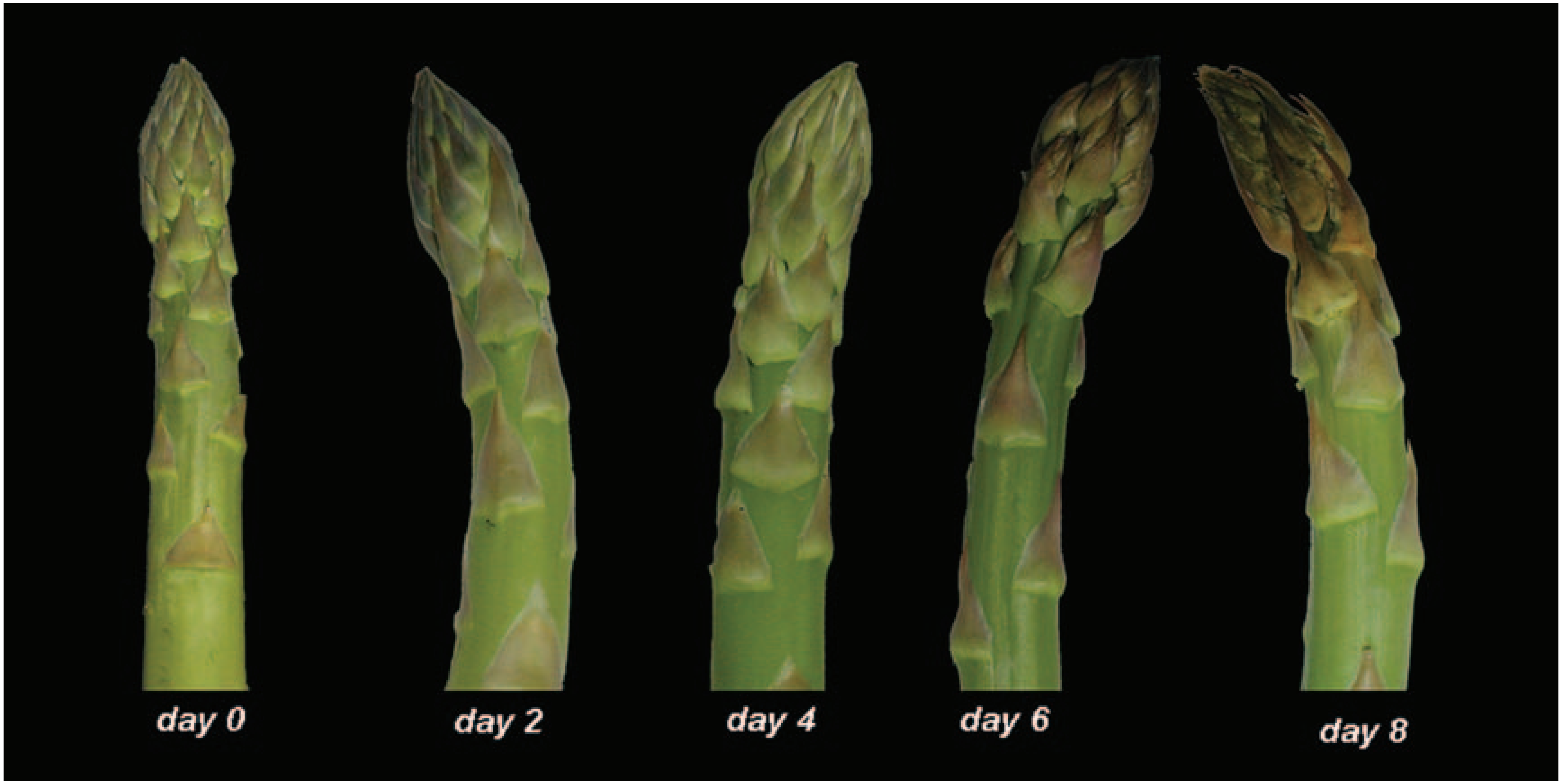

Figure 7.5. Appearance of asparagus ‘Guelph Millennium’ stored for 8 days at 20°C. Asparagus spears maintain an acceptable visual quality during 2 days, and after approximately 4–6 days the spears develop an objectionable brownish-green color with open and very dry brackets.

LETTUCE

Scientific Name: *Lactuca sativa* L. var. *capitata* L.
Family: Asteraceae

Quality Characteristics

Boston lettuce is one of the most popular varieties in Western Europe, where it accounts for about 80% of lettuce consumption. It is known as 'Sla' in Holland, 'Laitue' in France, and 'Round' in England. In North America this type of lettuce is gaining some popularity, and it is known as Butterhead or Bib but is most often called Boston lettuce. Boston lettuce, unlike other types of lettuce, such as Iceberg, Romaine, or leaf, forms open heads with softer leaves and has a much smoother and delicate texture. Therefore, compared to other types of lettuce, Boston lettuce is damaged much more easily due to its exceptionally tender leaves. It was reported that crushing and bruising resulted in postharvest losses of about 28% of fresh harvested Butterhead lettuce (Boonyakiat 1999). In addition, Boston lettuce is very susceptible to water loss and mechanical damage during storage or transportation. Lettuce in general, and tender leaf lettuce such as Boston in particular, should not be overpacked into cardboard boxes, as this may result in unnecessary crushing and bruising, which may hasten water loss and the development of decay during storage (Risse 1981). High-quality lettuce should be free from browning, and outer leaves should have a bright, light green color while inner leaves should be light greenish-yellow. Boston lettuce leaves should be crisp and turgid (Salveit 2004b).

Overall, lettuce contains approximately 96% water, 2.0% carbohydrates, 1.0% proteins and 1.4% fiber, 4–24 mg of vitamin C, 56 μg of folate and 330 IU of vitamin A, and 158 mg potassium per 100 g of fresh weight, as well as other vitamins and minerals in minor concentrations (Albrecht 1993; Marlett and Vollendorf 1993; Nicolle et al. 2004; USDA 2006). Lettuce also contains carotenoids and vitamin E. Lutein and β-carotene were the main carotenoids found in Butterhead, Batavia, and Oak Leaf lettuce cultivars (Kimura et al. 2003; Nicolle et al. 2004). Field-grown lettuce has in general a higher content of flavonoids, lutein, and carotenoids than greenhouse-grown lettuce, most likely due to the reduced exposure to sunlight and lower temperatures normally encountered in greenhouse production (Kimura et al. 2003; Romani et al. 2002). A higher concentration of β-carotene and lutein was also found in lettuce grown during summer compared to lettuce grown during fall (Mou 2005). In mature leaves of Boston lettuce, carotenoid content was two to four times greater than in immature leaves (Azevedo-Meleiro and Rodriguez-Amaya 2005).

Optimum Postharvest Handling Conditions

Vacuum-cooling is considered the best method for pre-cooling lettuce. Forced-air cooling and hydro-cooling can also be used when vacuum-cooling is not available. However, while forced-air cooling is less effective than vacuum-cooling, hydro-cooling is only recommended for non-head lettuces, as the water retained in the head may cause premature development of decay (Salveit 2004b). Compared to direct cold storage (no pre-cooling), vacuum-cooling helped to control weight loss in lettuce stored for 2 weeks at 0°C (Turk and Celik 1993), and maintained firmness, ascorbic acid, and chlorophyll content in lettuce stored for 2 weeks at 1°C (He et al. 2004). Vacuum-cooling was reported to prevent the development of pink rib and heart-leaf injury in Iceberg lettuce stored for 2 weeks at 2°C (Martínez and Artés 1999). Vacuum-cooling followed by storage and display at 5°C reduced leaf-end discoloration, wilting, and weight loss compared to storage and display at 10°C (Stanley 1989). However, in order to maintain its best quality, lettuce should be promptly vacuum-cooled and held at 0°C and 98–100% relative humidity immediately after cooling (Risse 1981; Salveit 2004b).

Film liners or individual polyethylene film wraps may be used to maintain the lettuce heads with a fresh appearance. However, such films should be perforated or be permeable in order to avoid development of injurious atmosphere or to avoid excessively high humidity and excessive condensation on the lettuce surface, which can promote decay development (Salveit 2004b). Nonperforated, sealed polypropylene bags of adequate gas permeability may also be used to reduce weight loss and wilting and to maintain the quality of Iceberg lettuce (Artés and Martínez 1996; Brecht et al. 1986; Martínez and Artés 1999). The use of misting systems during consumer display has also been demonstrated to reduce weight loss, maintain crispness and firmness, and delay ascorbic acid degradation in lettuce (Dieckmann et al. 1993).

The level of ethylene around lettuce during normal commercial operations (0.11–0.85 µl/liter) may also contribute to accelerated loss of quality due to the development of russet spotting. This physiological disorder is induced by exposure to ethylene and is characterized by the development of small reddish-brown spots along both sides of the midribs. Russet spotting is aggravated if lettuce is handled at temperatures higher than 0°C (Manleitner et al. 2001). Therefore, reducing the ethylene levels around lettuce will delay russet spotting and leaf browning, resulting in lower levels of deterioration. Ethylene reduction from 1.0 to 0.005 µl liter^{-1} increased postharvest life of Iceberg lettuce stored at 20°C by about 250% with 10% trimming loss, and increased postharvest life at 0°C by 200% (Kim and Wills 1995).

Temperature Effects on Quality

Undesirable high temperatures during handling or storage of lettuce accelerate respiration, speed up senescence, cause leaf yellowing, and increase loss of moisture. After harvest, lettuce may be exposed to high temperatures due to inadequate pre-cooling and/or handling temperatures, and by solid, tight loads that restrict cold air from circulating around and all over the load. Of all fresh fruits and vegetables arriving at the New York market, lettuce was reported to have the highest number of shipments rejected due to high levels of decay, physiological disorders, and injuries caused by exposure to inadequate environmental conditions during handling (Ceponis et al. 1985).

In dark green leaf lettuce, browning developed after 14 days at 5°C (Rivera et al. 2006). Other discoloration symptoms such as russet spotting, midrib browning, and leaf-end discoloration also increased as the storage time and temperature increased (Manleitner et al. 2001; Risse 1981). For Iceberg lettuce stored at 6°C, visual quality started to decline after 7 days of storage and was considered unacceptable after 21 days mainly due to rib discoloration and development of decay (Schofield et al. 2005). L* value of Boston lettuce stored at temperatures above 5°C increased during storage, meaning that a shift in the color from dark green to a more light green color occurred, possibly due to yellowing of the leaves (Nunes and Emond 2003a). On the other hand, L* value of lettuce stored at 0 or 5°C did not change significantly throughout storage. When lettuce was stored at 20°C hue value decreased sharply, and after 4 days the leaves appeared more yellow than green. Hue value of lettuce stored at 10 or 15°C also decreased during storage as a result of a slight discoloration of the leaves from a yellowish-green to a greenish-yellow color. Hue of lettuce stored at 0 or 5°C did not change significantly during storage, and chroma decreased mostly in lettuce stored at 10, 15, and 20°C (Nunes and Emond 2003a).

Firmness of Boston lettuce decreased during storage, regardless of the storage temperature. With increasing storage time and temperature lettuce leaves became less turgid, wilted, and softer, particularly in lettuces stored at temperatures higher than 5°C. After approximately 3–4 days, lettuce stored at 20°C attained an objectionable softness, and after 6 days lettuce stored at 15°C was no longer acceptable due to severe softening of the leaves. Lettuce heads stored at 0 or 5°C maintained a good firmness and turgid appearance up to 12 or 10 days, respectively (Nunes and Emond 2003a). Iceberg lettuce stored continuously at 2.2°C for 7 days had the best appearance and lowest wilting and decay compared to lettuce that was subsequently stored for 3 days at 10°C (Risse 1981).

Decay in Boston lettuce increased throughout storage, regardless of the storage temperature. However, the development of decay was significantly greater in lettuce stored at 10, 15 or 20°C compared to storage at 0 or 5°C. After approximately 10, 7 and 3 days decay severity attained objectionable values in lettuce stored at 10, 15 or 20°C, respectively. Decay in Boston lettuce was most likely due to the development of bacterial soft rot, as the lesions had a soft and slimy appearance (Nunes and Emond 2003a). In fact, bacterial soft rot was reported to be the most detrimental disorder of lettuce transported to the New York market (Ceponis et al. 1985).

In general, as storage temperature increases lettuce quality decreases (Brecht et al. 1973; Kim and Wills 1995; Nunes and Emond 2003a). For example, it was reported that Iceberg lettuce maintained an acceptable quality when stored for 4 weeks at 0°C, but after 2 weeks at 3°C quality was objectionable due to severe wilting (Parsons et al. 1960). For Boston lettuce stored at 0°C, wilting was considered the main quality factor that limited postharvest life. Wilting attained objectionable values and reduced the postharvest life of lettuce to 11 days (Nunes and Emond 2003a). Unlike Boston lettuce, the main causes of deterioration of Iceberg lettuce stored at 0°C were browning, rotting, and russet spotting (Kim and Wills 1995). Brown discoloration, loss of firmness, wilting, and yellowing of the leaves were the main quality factors that limited the postharvest life of Boston lettuce stored at 15°C to 2 or 3 days (Nunes and Emond 2003a). In Iceberg lettuce stored at 20°C, browning and decay of the outer leaves and browning of the inner leaves were considered the main causes of deterioration. After only 1 day at 20°C the outer leaves started to show wilting, and after 9 days 70% of the leaves were yellow and severely wilted. Consequently, Iceberg lettuce had a postharvest life three to four times shorter at 20°C than at 0°C (Kim and Wills 1995).

Weight loss of Iceberg lettuce significantly increases with increasing storage time and temperature. For example, for lettuce stored at 0°C weight loss reached 4.4% after 2 weeks and increased further to 9.6% after 6 weeks (Parsons et al. 1960). When lettuce was stored at 3°C weight loss increased to 5.6% after 2 weeks and reached 11.2% after 6 weeks. After 4 weeks at 10°C weight loss of lettuce was as high as 8.8%. Extended storage of lettuce, even at 0°C, contributed to extremely high values of weight loss, resulting in severe wilted appearance (Parsons et al. 1960). Weight loss of Boston lettuce increased during storage at all temperatures, but never attained such critical values, presumably due to the high humidity levels (95%) that were maintained around the lettuce (Nunes and Emond 2003a). After approximately 2 days, Iceberg lettuce stored at 20°C attained a 3.7% weight loss, which is the maximum weight loss before lettuce is considered unacceptable for sale (Kays and Paull 2004; Robinson et al. 1975). Boston lettuce stored at 0 or 5°C attained the maximum acceptable weight loss after approximately 9–13 days of storage, respectively. Head softness and leaf wilting in lettuce stored at 0°C were noticeable after 10–12 days of storage, which corresponded to approximately 2.7–3% weight loss. In lettuce from a second harvest stored at 0°C weight loss attained 3.7% after 9 days, and wilting was evident after only 11 days (approximately 5% weight loss); softness started to be objectionable after 12 days when weight loss was 5.5% (Nunes and Emond 2003a). Likewise, head lettuce attained a weight loss of about 3.5–4% after storage for 2 weeks at 0°C (Turk and Celik 1993). For Boston lettuce stored at 5°C, wilting became objectionable after 7–12 days, depending on the time of harvest. At that time, lettuce stored at 5°C had lost approximately 3.0–3.2% of its initial weight (Nunes and Emond 2003a). Other types of lettuce—for example, Iceberg—seemed to have much lower levels of weight loss during storage compared to Boston lettuce. Weight loss of Iceberg lettuce was only about 0.4% after storage for 2 weeks at 1°C and 85% relative humidity (He et al. 2004). However, after 2 weeks at 2°C weight loss of 'Salinas' Iceberg lettuce had reached approximately 6.3%, and after transfer to 12°C for 2.5 days weight loss increased to about 8.4% (Martínez and Artés 1996).

Development of wilting is greatly associated with loss of moisture. When moisture loss from lettuce increases, signs of wilting become apparent when loss of water reaches a critical level that is characteristic of the particular lettuce type. For instance, Iceberg lettuce stored for 2 weeks at 2°C showed objectionable wilting levels when weight loss attained approximately 6%. After transfer to 12°C for 2.5 days weight loss increased further, resulting in severe wilting (Artés and Martínez 1996). For Boston lettuce, wilting was extremely fast during storage, particularly when stored at high temperatures. Even when stored at 0°C, wilting was relatively fast, and after approximately 10 days the external leaves already showed moderate signs of wilting. After approximately 3 days at 20°C Boston lettuce attained an objectionable wilting, the leaves were very limp and flaccid, and weight loss at this time ranged from 5 to 6%. It was found that for Boston lettuce, the symptoms related to loss of moisture, such as wilting and loss of head firmness, become apparent when weight loss reaches approximately 2.7% (Nunes and Emond 2003a).

Film wrapping is one of the most effective means to reduce weight loss and the wilted appearance that results from loss of moisture in lettuce heads. For example, weight loss in wrapped lettuce stored for 2 weeks at 5°C was significantly lower (less than 0.5%) compared to weight loss in unwrapped lettuce heads (more than 2%) stored under the same conditions. Furthermore, after exposure to 20°C for 2 days weight loss of wrapped lettuce was much lower (less than 2%) than that of unwrapped lettuce (more than 7%) (Brecht et al. 1986).

During the postharvest period, simultaneously with changes in appearance, compositional changes also take place and are, like changes in appearance, greatly affected by temperature. For example, Iceberg lettuce stored at 1°C was reported to have an initial ascorbic acid content of 3.6 mg/100 g that was reduced to 2.9 mg/100 g after 2 weeks of storage (He et al. 2004), which corresponded to a decrease in the initial ascorbic acid content of about 18%. In 'Butter Crunch' Boston-type lettuce stored at 7°C, ascorbic acid content decreased during storage and after 1 and 2 weeks ascorbic acid retention was 40 and 16%, respectively (Albrecht 1993). Ascorbic acid uptake was observed when dark green leaf lettuce was hydro-cooled by immersion in cold water containing 1% ascorbic acid. Initial total ascorbic acid content of the lettuce immersed in cold water with added ascorbate increased by 318% after 1 day of storage at 5°C, and levels were maintained higher than the initial values for up to 7 days. Nevertheless, ascorbic acid content decreased over time, and after 21 days at 5°C the ascorbic acid content of the ascorbate-treated lettuce was not significantly different from that of the nontreated lettuce. For dark green lettuce stored for 14 days at 5°C, ascorbic acid content decreased by 39 and 66% after 7 and 14 days, respectively (Rivera et al. 2006).

Changes in the chlorophyll content of lettuce during storage normally accompany changes in the visual color of lettuce from dark green to yellowish-green. For instance, chlorophyll content of Iceberg lettuce declined very quickly, and after 2 weeks at 1°C the lettuce had lost approximately 60% of its initial chlorophyll content (He et al. 2004).

Time and Temperature Effects on the Visual Quality of 'Flandria' Boston-Type Lettuce

'Flandria' lettuce shown in Figures 7.6–7.10 was harvested when the heads were well formed and with an average weight of 160 grams per head, from a greenhouse hydroponic commercial operation in Mirabel, Quebec, Canada, during the fall season (i.e., October–November). Promptly after harvest, fresh lettuces were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

'Flandria' lettuce becomes less bright green and develops some yellowing of the leaves with increasing storage time and temperature (Figures 7.6–7.10). Signs of discoloration, such as loss of green color, yellowing, and browning of the outer leaf margins, develop during storage, particularly in lettuce stored at temperatures higher than 5°C. After approximately 1–2 days at 20 or 15°C, respectively, the color of 'Flandria' lettuce is considered unacceptable due to yellowing and browning of the leaf edges (Figures 7.9 and 7.10).

However, color of lettuce stored at 0 or 5°C remains satisfactory for up to 15 or 8 days, respectively (Figure 7.6 and 7.7). Leaf browning increases throughout storage despite the storage temperature, but the increase in browning of the leaf edges is more important in lettuce stored at 10, 15, and 20°C, compared to other storage temperatures. After approximately 8, 5, and 4 days browning becomes objectionable in lettuce stored at 10, 15, and 20°C, respectively, while browning in lettuce stored at 0 or 5°C is negligible (Figure 7.6–7.10).

Changes in the color of 'Flandria' lettuce stored at temperatures higher that 5°C are faster and more accentuated than when the lettuce is held at 0°C, and after a few days the color becomes less bright, less green, and more dull and yellowish.

Wilting is the main quality factor that limits the postharvest life of lettuce stored at all temperatures. 'Flandria' lettuce stored at 0°C shows severe wilting after 25 days of storage (Figure 7.6), while after approximately 8–11 days at 5°C wilting of the leaves becomes objectionable (Figure 7.7). In 'Flandria' lettuce stored at 10, 15, or 20°C wilting develops much faster than at 0 or 5°C, and after only 2–5 days the leaves are completely wilted (Figures 7.8–7.10).

Overall, in 'Flandria' lettuce wilting and changes in color, such as yellowing of the leaves and browning at the leaf edges, are the most important visual quality factors that limit the postharvest life of the lettuce. Increasing the storage time and temperature results in accelerated loss of quality. 'Flandria' lettuce stored at 0°C maintains a good quality for longer periods of time (22 days) than lettuce stored at higher temperatures. Lettuce stored at 5 and 10°C retains an acceptable visual quality for up to 18 and 4 days, respectively, but quality deteriorates very quickly afterward. 'Flandria' lettuce postharvest life is reduced to only 1 day when exposed to 15 or 20°C.

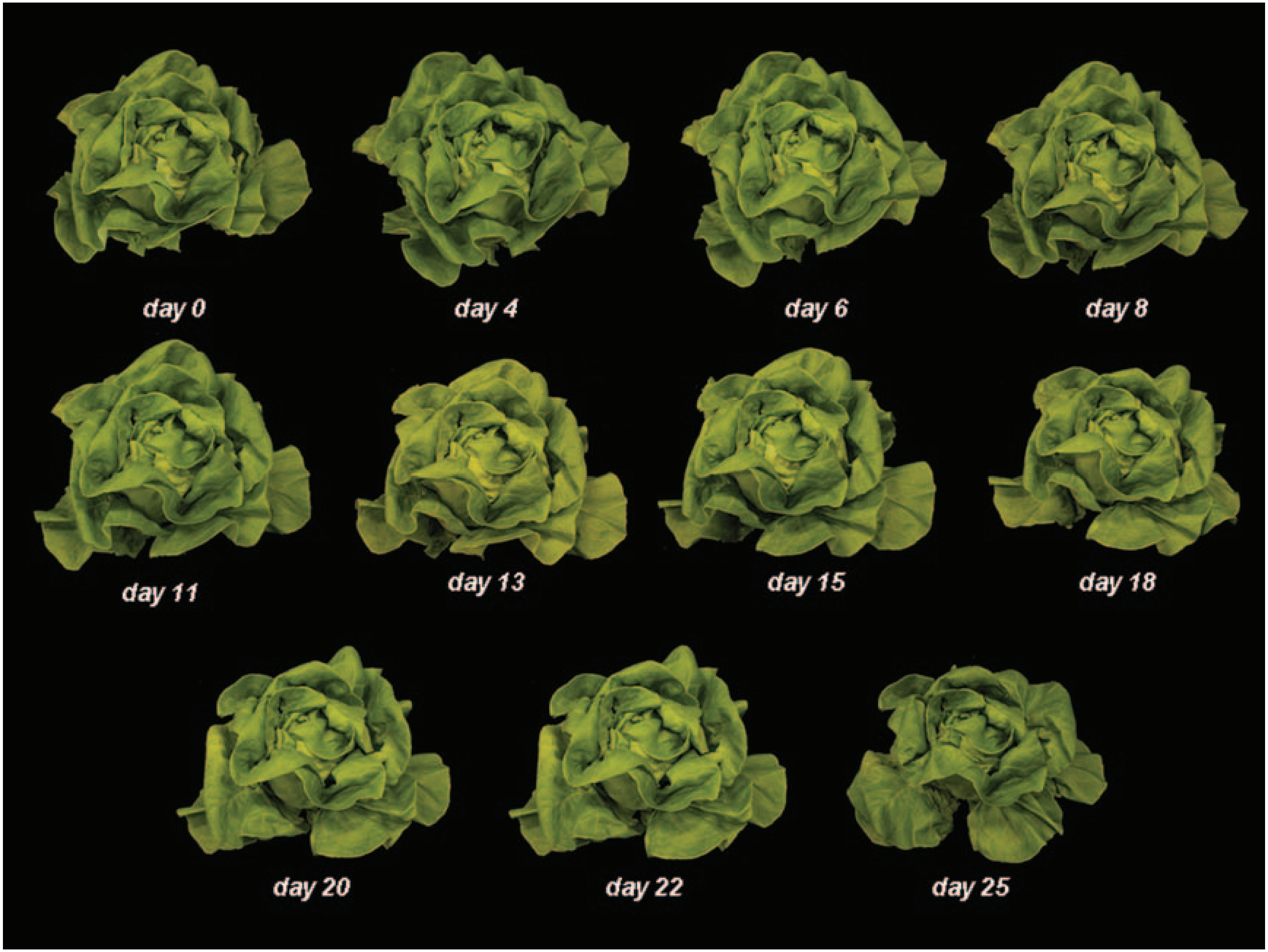
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Figure 7.6. Appearance of 'Flandria' lettuce stored for 25 days at 0°C. Lettuce outer leaves start to develop some minor yellowing after approximately 13–15 days at 0°C. After 25 days the leaves are extremely wilted and flaccid.

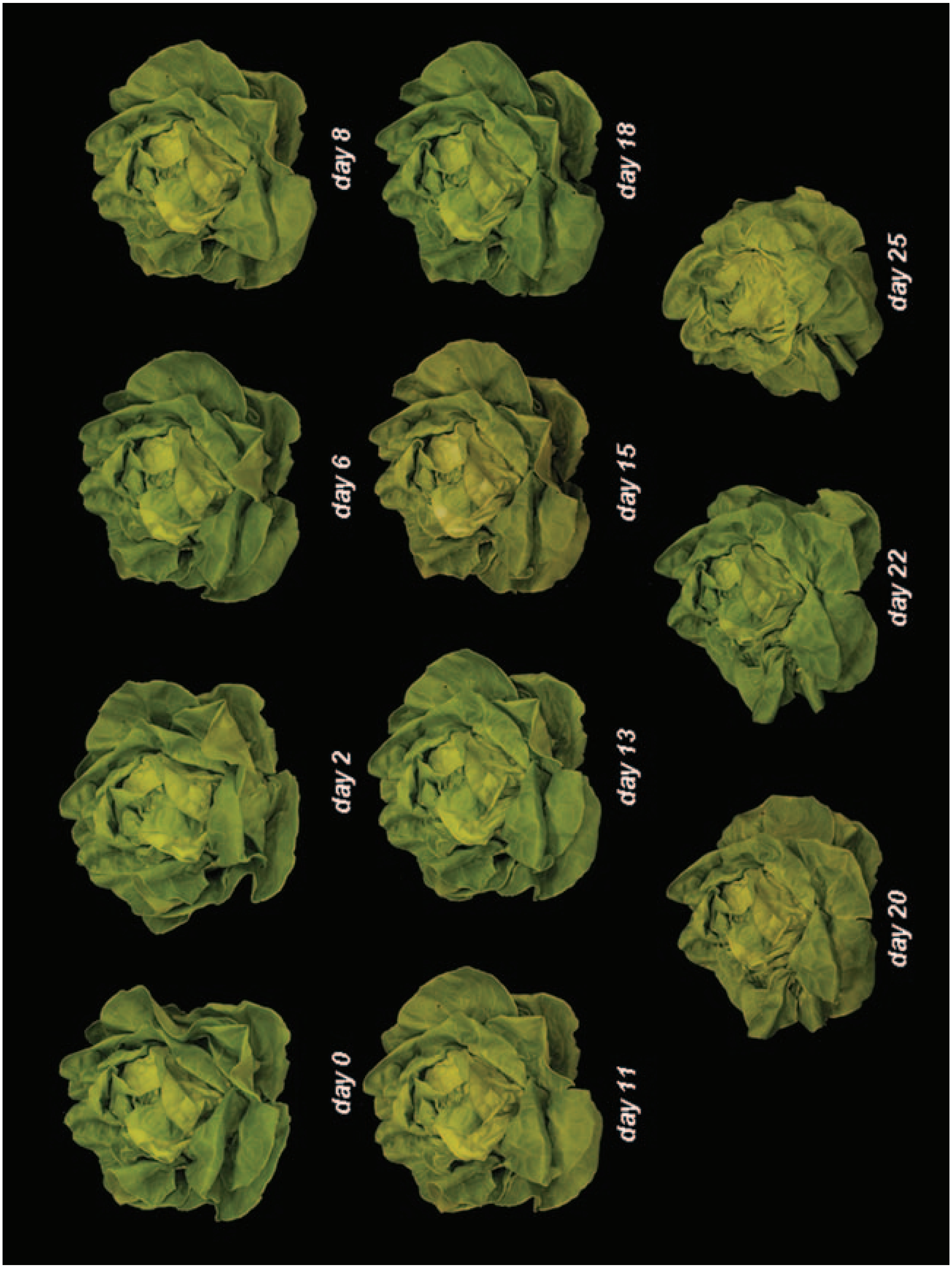
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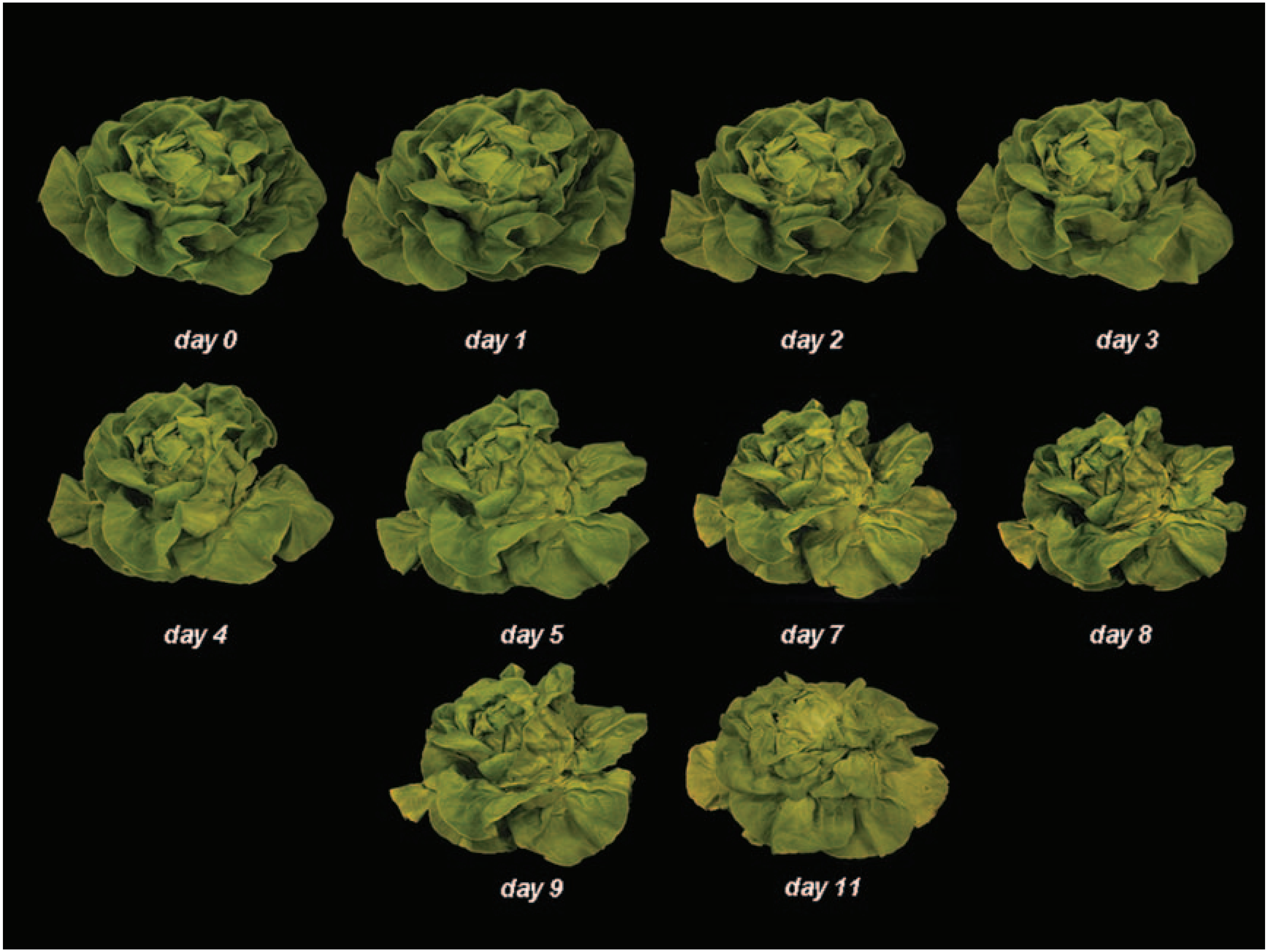
Figure 7.7. Appearance of 'Flandria' lettuce stored for 25 days at 5°C. Wilting, softening, and yellowing of the leaves become objectionable after approximately 8–11 days. After 25 days the leaves are extremely wilted and flaccid.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day 9
day 11

Figure 7.8. Appearance of ‘Flandria’ lettuce stored for 11 days at 10°C. After 4 days loss of turgidity, flaccidity, wilting, and yellowing of the leaves are evident, and they become severe after approximately 7 days.

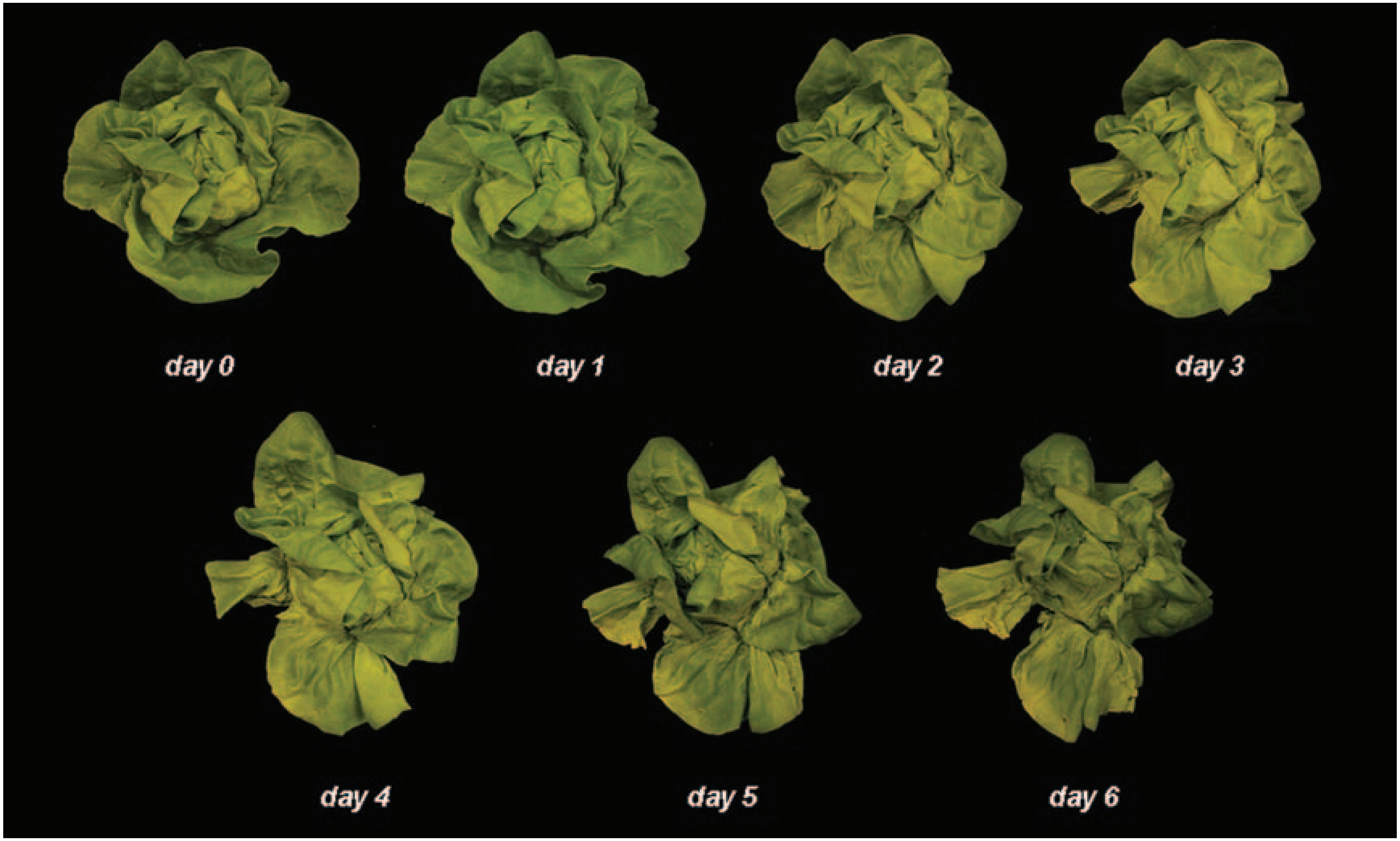
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Figure 7.9. Appearance of 'Flandria' lettuce stored for 6 days at 15°C. Softening, wilting, and yellowing of the leaves becomes unacceptable after 2–3 days of storage.

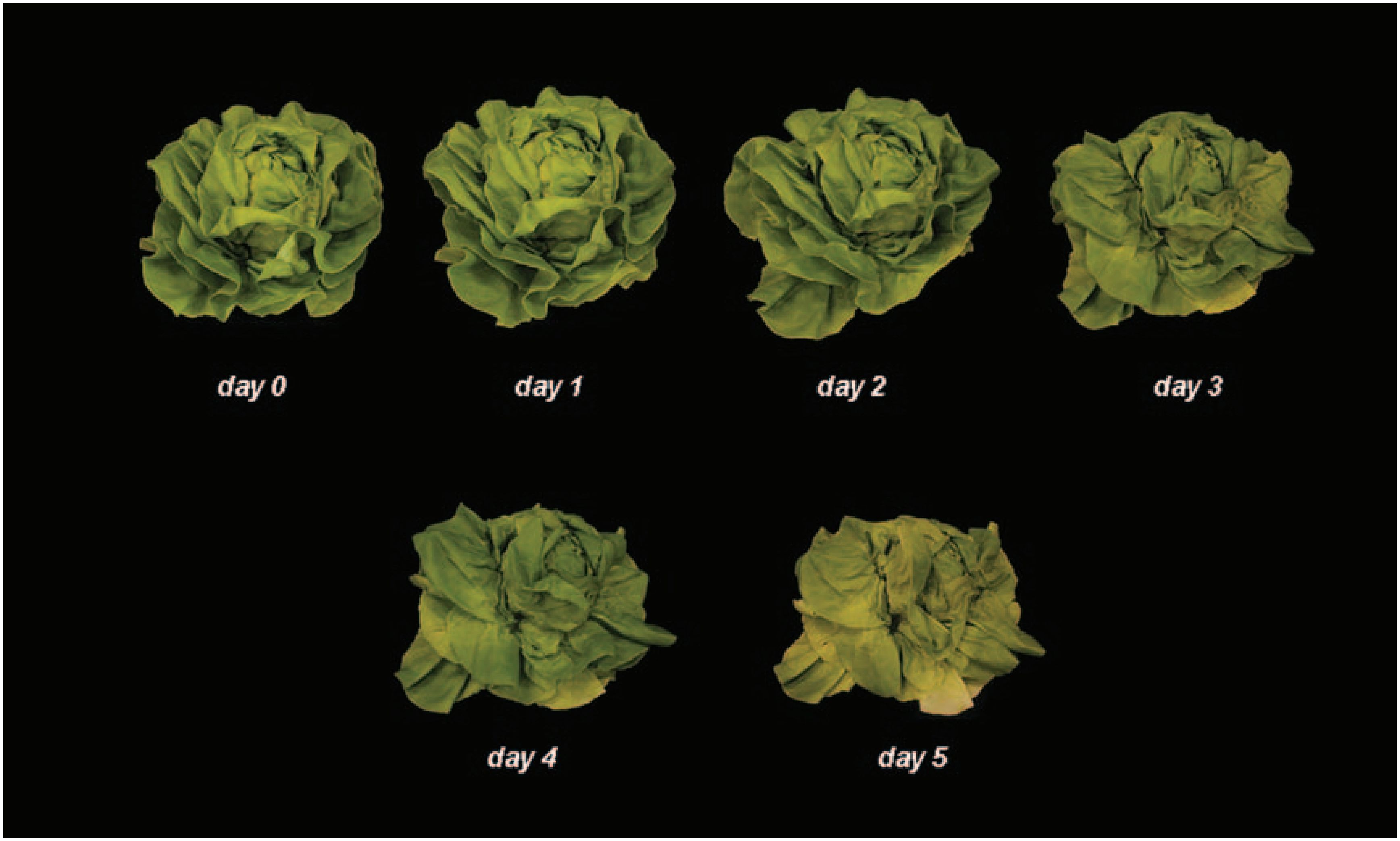
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Figure 7.10. Appearance of 'Flandria' lettuce stored for 5 days at 20°C. After approximately 3 days lettuce shows severe wilting, softening, and yellowing.

WITLOOF CHICORY

Scientific Name: *Cichorium endivia*
Family: Araliaceae

Quality Characteristics

Witloof chicory (white-leaf chicory), also known as Belgian endive, has been used in Western European countries for a long time due to its eating qualities and particular taste. Witloof chicory is a young bud (chicon) consisting of leaves and a young elongated shoot. The chicons are grown by maintaining the roots in a hydroponic system and forcing them to sprout in the dark at temperatures between 14 and 23°C, depending on the physiological age of the roots. The chicon sprouts are then ready to harvest after approximately 23 days (Den Outer 1989). The young whitish chicons grown from forced chicory roots have long been used as a fresh vegetable, particularly in Belgium, France, and the Netherlands, where they are consumed regularly during winter and spring as a leafy salad vegetable. Although popularity has been increasing in North America, witloof chicory is not greatly appreciated due to its particular bitter taste and is still considered by many consumers to be a gourmet item. Owing to its high retail price, witloof chicory is usually purchased on an occasional basis (Corey et al. 1990; Hill 2000; Rubatzky and Salveit 2004; Ryder 1979). Inadequate retail display conditions (i.e., exposure to high temperatures and light) that are often encountered in produce departments lead to a poor quality chicon, and thus reduce the chance of further purchases from first-time consumers. Bad temperature management, combined with light exposure during witloof chicory retail display, results in greening of the leaves and development of a bitter taste. Currently, most packages allow exposure to light, and as a result contribute to a significant reduction in chicon shelf life.

Quality of witloof chicory is based primarily on size, compactness, and shape of the chicon, and color of the leaves. Open and loosely packed leaves are indications of a bad quality chicon (Tan and Corey 1990). Therefore, after trimming the outer leaves, witloof chicory heads should be firm and very tight, with only two outer leaves visible. Leaves should be pure white with creamy-yellow points and not have any torn, greenish leaves or reddish discoloration. Witloof chicory cultivars vary in flavor and bitterness, and when exposed to light chicons rapidly turn green and increase in bitterness (Rubatzky and Salveit 2004; Ryder 1979).

Overall, witloof chicory contains approximately 95% water, 3.0% carbohydrates, 1.0% proteins and 3.1% fiber, 7 mg of vitamin C, 142 µg folate, 2,167 IU of vitamin A, and between 18 and 52 mg calcium per 100 g of fresh weight, as well as other vitamins and minerals in minor concentrations (Ryder 1979; USDA 2006).

Optimum Postharvest Handling Conditions

Witloof chicory can be pre-cooled by different methods. Although hydro-cooling is very effective in pre-cooling the chicons, water may be retained inside the chicon and accelerate undesirable quality changes such as chicon opening and leaf browning (Ryder 1979). On the other hand, vacuum-cooling may cause a 2–3% reduction in the fresh weight of the chicon due to loss of moisture, while forced-air cooling is not suitable to cool-packed witloof chicory. Even though conventional room-cooling is less effective than the other pre-cooling methods, it is often used due to economic reasons (Rubatzky and Salveit 2004). Storage at 0°C with high relative humidity levels (above 95%) and light excluded are required environmental conditions to optimize witloof chicory quality and extend postharvest life. Under optimum conditions, witloof chicory has an expected postharvest life of about 2–3 weeks (Salveit 2004a).

Temperature Effects on Quality

Color of witloof chicory is greatly influenced by the postharvest environmental conditions, and visual appearance of the chicon deteriorates faster when stored under adverse conditions. Red discoloration seems to be an important quality disorder of witloof chicory resulting from cell damage and subsequent oxidation of phenolic compounds during storage. A clear positive correlation exists between the stem length and the development of red discoloration (Vanstreels et al. 2002; Verlinden et al. 2001). Furthermore, the probability of red discoloration development increases with increasing weight of the chicon and the storage time. After 10 days at 1°C, chicons showed a large amount of red discoloration, while at 5 and 12°C there was significantly less red discoloration (Vanstreels et al. 2002). L* value of the chicons decreased during storage, regardless of the temperature, indicating that the color became darker. After 18 or 20 days of storage the tip of chicons was darker (lower L* value) than at the time of harvest, meaning that color turned from a light creamy-yellow to a darker greenish-yellow. There was also a slight increase in the hue value (a shift from creamy-yellow to greenish-yellow color) of the chicons stored at all temperatures until day 10, followed by a decrease until day 14. After 16 days chicons stored at 10, 15, or 20°C showed a significant decrease in their hue value, meaning a shift in color from a greenish-yellow to a brownish-yellow, most likely due to the development of browning on the leaf edges. A similar trend was observed for chroma, which increased until day 10, followed by a decrease henceforward. Overall, the color of the chicons changed from a vivid very light creamy-yellow to a dull greenish-yellow after the end of storage (Nunes and Emond 2003b).

Browning of witloof chicory leaves increased throughout storage, despite the storage temperature. However, the increase in browning on the leaf edges was more important in chicons stored at 15°C compared to other storage temperatures. In fact, after 10 days, browning became objectionable in chicons stored at 15°C, while in witloof chicory stored at other temperatures the maximum acceptable browning was attained after approximately 15–16 days, depending on the storage temperature (Nunes and Emond 2003b). Apparently, during the first 4 days the red area in chicon leaves increases faster than the brown color, and after the fourth day increase in browning is more accentuated than red discoloration. Temperatures in the range of 10–18°C during the first 2 days after harvest resulted in more red and brown discoloration, compared to storage at temperatures between 2 and 5°C. The higher the humidity levels around the chicons, the faster the development of red or brown discoloration. Temperature fluctuations that often occur during handling and storage of witloof chicory also result in increased red and brown discoloration (Zhang et al. 2003).

Firmness of chicons decreased during storage, regardless of the storage temperature. However, increased softening of the buds was more important in witloof chicory stored at 15 or 20°C. After approximately 13 days firmness of the chicons stored at 15 or 20°C became objectionable, whereas for those stored at 5 or 10°C softness became objectionable after approximately 13 days. Witloof chicory stored at 0°C maintained a good firmness up to 18 days of storage. Loss of firmness was paralleled by development of wilting, which followed a very similar trend to chicon softening. Wilting was more important in chicons stored at 15 or 20°C than at 0, 5, or 10°C. After approximately 12 days at 15 or 20°C, wilting became objectionable and the chicons started to show moderate signs of flaccidness. Wilting became objectionable after 14 days for chicons stored at 5 or 10°C, and after 18 days for chicons stored at 0°C (Nunes and Emond 2003b).

Decay increased slightly during storage but attained objectionable levels only for witloof chicory stored at 15 or 20°C. In chicons stored at lower temperatures decay never reached unacceptable levels, even after 11 or 25 days of storage (Nunes and Emond 2003b). Simultaneously with development of decay, an objectionable musty-like aroma was sensed during storage of witloof chicory and limited the postharvest life of the chicons stored at temperatures higher than 0°C. After approximately 9 days, chicons stored at 15°C developed an unpleasant aroma, while in chicory stored at 0°C aroma was still acceptable after 14 days. Taste of witloof chicory also deteriorated very quickly, and as the leaves turned greener they became bitter, particularly in chicons stored at temperatures higher than 5°C. After 8 days, the taste of witloof chicory leaves stored at 20°C was very disagreeable, while the taste of the chicons stored at 0°C was acceptable up to 14 days (Nunes and Emond 2003b).

It seems that temperature has a greater influence on chicory greening than light exposure. Chicory exposed to 0°C in the presence of light showed little or no greening, but as the temperature was raised a significant increase in leaf greening was observed (Rubatzky and Salveit 2004). Leaf growth was also accelerated when chicory was stored at temperatures higher than 10°C, compared to storage at 2 or 5°C (Zhang et al. 2003).

Weight loss of witloof chicory was highest after 18 days at 20°C, when compared to the weight loss of chicons stored at 0 or 5°C for the same period of time. However, even when stored at 20°C for 18 days weight loss of witloof chicory did not exceed a maximum of approximately 4%. Reduced weight loss resulted most likely from the high humidity levels maintained inside the cold rooms as well as from the packaging system. On the other hand, wilting of the leaves (one of the signs that the loss of moisture from the chicon leaves started to be objectionable) became objectionable after approximately 14 days at 0, 5, and 10°C, and after approximately 12 days at 15 and 20°C. The percentage of weight loss that corresponded to these times ranged from approximately 1.0–2.5%, depending on the temperature. Therefore, a weight loss as low as 2.5% should be considered the maximum acceptable for witloof chicory before wilting becomes objectionable (Nunes and Emond 2003b).

Storage temperature also affects the compositional characteristics of witloof chicory, but little information is available on this subject. For example, total flavonol glycosides content is reduced by approximately 55% after storage for 7 days at 1°C (Dupont et al. 2000), while storage for 2 days at 4°C contributed to a 25% reduction in witloof chicory total phenolic content and antioxidant capacity (Mayer-Miebach et al. 2003).

Time and Temperature Effects on the Visual Quality of 'Focus' Witloof Chicory

'Focus' witloof chicory shown in Figures 7.11–7.17 was harvested at the compact creamy-yellow stage with outer leaves tightly closed from a commercial operation in Saint-Clement, Quebec, Canada, during the fall season (i.e., October). Promptly after harvest, fresh chicons were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Color of ‘Focus’ witloof chicory changes during storage from a creamy light yellow to a creamy dark greenish-yellow, and in some cases development of a reddish-brown discoloration is also evident in the outer leaves or cut edge, particularly in chicons stored at 20°C. Besides changes in color, leaves grow and separate, resulting in loss of chicon compactness (Figures 7.11–7.15). Storage at 20°C combined with light exposure results in accelerated leaf development (Figures 7.16 and 7.17).

Changes in color from a light yellow to a light greenish-yellow, development of leaf edge browning, and wilting are the main visual quality limiting factors in witloof chicory stored at 0°C. From day 10 to day 12 the outer leaves start to show some browning of the edges, and after approximately 14 days browning becomes unacceptable. Simultaneously the chicon becomes softer to the touch, and the leaves appear wilted and more green (Figure 7.11).

Although witloof chicory stored at 5°C maintained an acceptable visual quality for up to 20 days of storage, color of the tip shifts from a pale creamy-yellow to a light greenish-yellow, and other nonvisual quality attributes, such as flavor and head softening, become unacceptable and reduce the witloof chicory postharvest life to approximately 12 days (Figure 7.12).

Witloof chicory stored at 10°C maintains an acceptable visual quality for up to 8 days of storage. After 10 days the outer leaves start to show some signs of browning, which becomes objectionable after 12 days. Besides leaf edge browning, the chicon softens and the leaves appear wilted. Color also changes from a pale creamy-yellow to a pale greenish-yellow, and opening of the leaves is also evident at this temperature (Figure 7.13).

In witloof chicory stored at 15°C, the most striking visual quality change is leaf growth that is accompanied by opening of the external leaves of the chicon and loss of compactness. Within 8–10 days of storage, the outer leaves start to grow and open, separating from the chicon head. After 20 days the tips of the outer leaves are grown and partially open. Development of a slight browning is also perceptible in the outer leaves after 6 days of storage, but this browning does not increase during the remaining storage period. Slight reddening of the cut edge develops after 16 days of storage (Figure 7.14). At this temperature other nonvisual quality attributes such as taste change very quickly, and even though the chicon shows acceptable visual quality, the taste is unpleasantly bitter.

When ‘Focus’ witloof chicory is stored at 20°C visual quality changes very quickly compared to storage at lower temperatures. The chicon outer leaves grow, open, and develop a brownish coloration at the edges. After approximately 8 days browning on the edge of the leaves starts to develop, and after 12 days the chicon is affected by severe browning. The outer leaves start to open after 10 days, and after 20 days leaf growth is evident and the chicon loses its compactness (Figure 7.15). However, at this temperature development of an extremely unpleasant bitter taste limits the postharvest life of chicory to 8 days.

When compared to storage in the dark, ‘Focus’ witloof chicory stored at 20°C and exposed to artificial light shows accelerated leaf growth and increase in green color development, presumably due to accelerated chlorophyll synthesis. After only 2 days at 20°C under light exposure, chicon outer leaves start to develop a light green color, simultaneously with slight head opening. The leaves continue to grow, and after 12 days under such conditions they are dark green, opened, and well developed (Figure 7.16). When chicory heads are exposed to a fluctuating natural light regimen, 12 hours under natural light plus 12 hours in the dark, color development is also very fast, but the rate of leaf growth is slower compared to chicons exposed to a continuous light regimen (Figure 7.17).

Overall, in ‘Focus’ witloof chicory changes in leaf color, such as greening and browning of the edges, leaf growth and opening, and thus loss of chicon compactness are the most important visual quality factors that limit the postharvest life of witloof chicory. Increasing the storage time and temperature results in accelerated loss of quality. ‘Focus’ witloof chicory stored at 0 and 5°C maintains a good quality for longer periods of time (12–20 days) than chicons stored at higher temperatures. Chicons stored at 10, 15, and 20°C retain an acceptable visual quality for 8, 6, and 2 days respectively, but quality deteriorates very quickly afterward. When witloof chicory is exposed to light at 20°C, quality deteriorates even faster, and after less than 2 days becomes unacceptable.

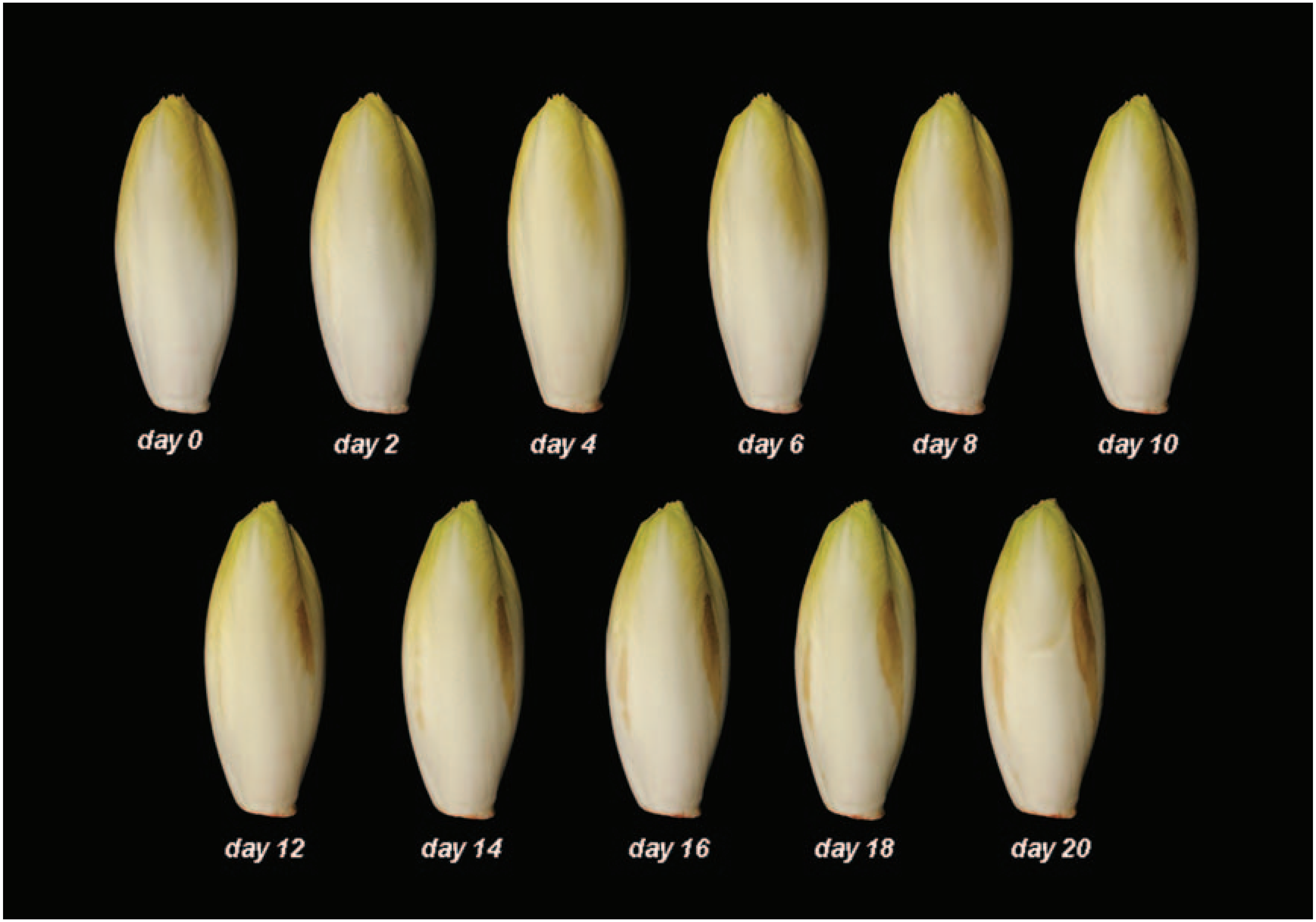
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Figure 7.11. Appearance of 'Focus' witloof chicory stored for 20 days at 0°C. From day 10 to day 12, the outer leaves start to show some browning on the edges, and after 20 days the chicon tips are slightly greener and leaf browning is evident.

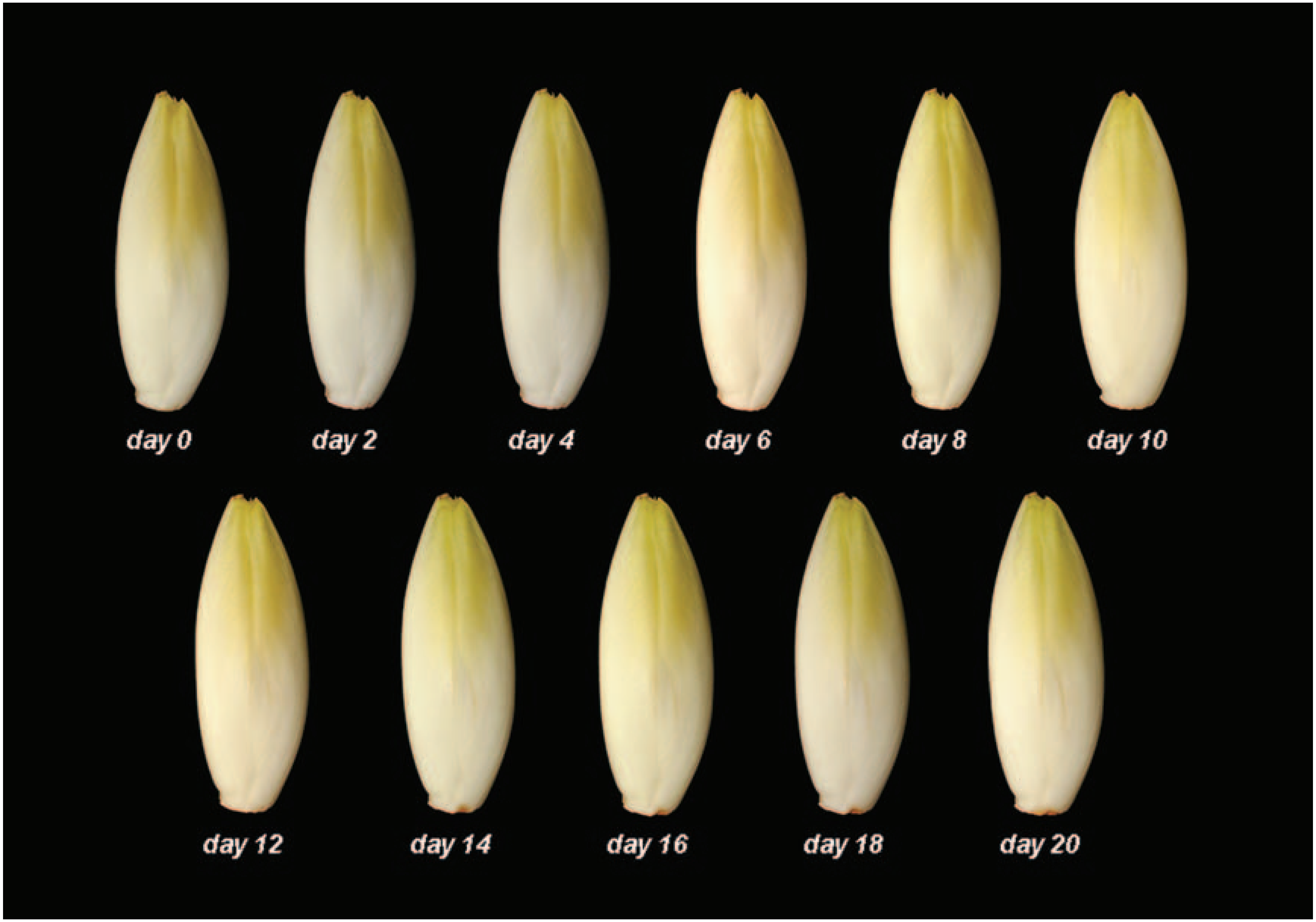
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Figure 7.12. Appearance of 'Focus' witloof chicory stored for 20 days at 5°C. The visual quality of the chicon remains acceptable up to 20 days, but the flavor becomes objectionable and reduces the postharvest life to approximately 12 days.

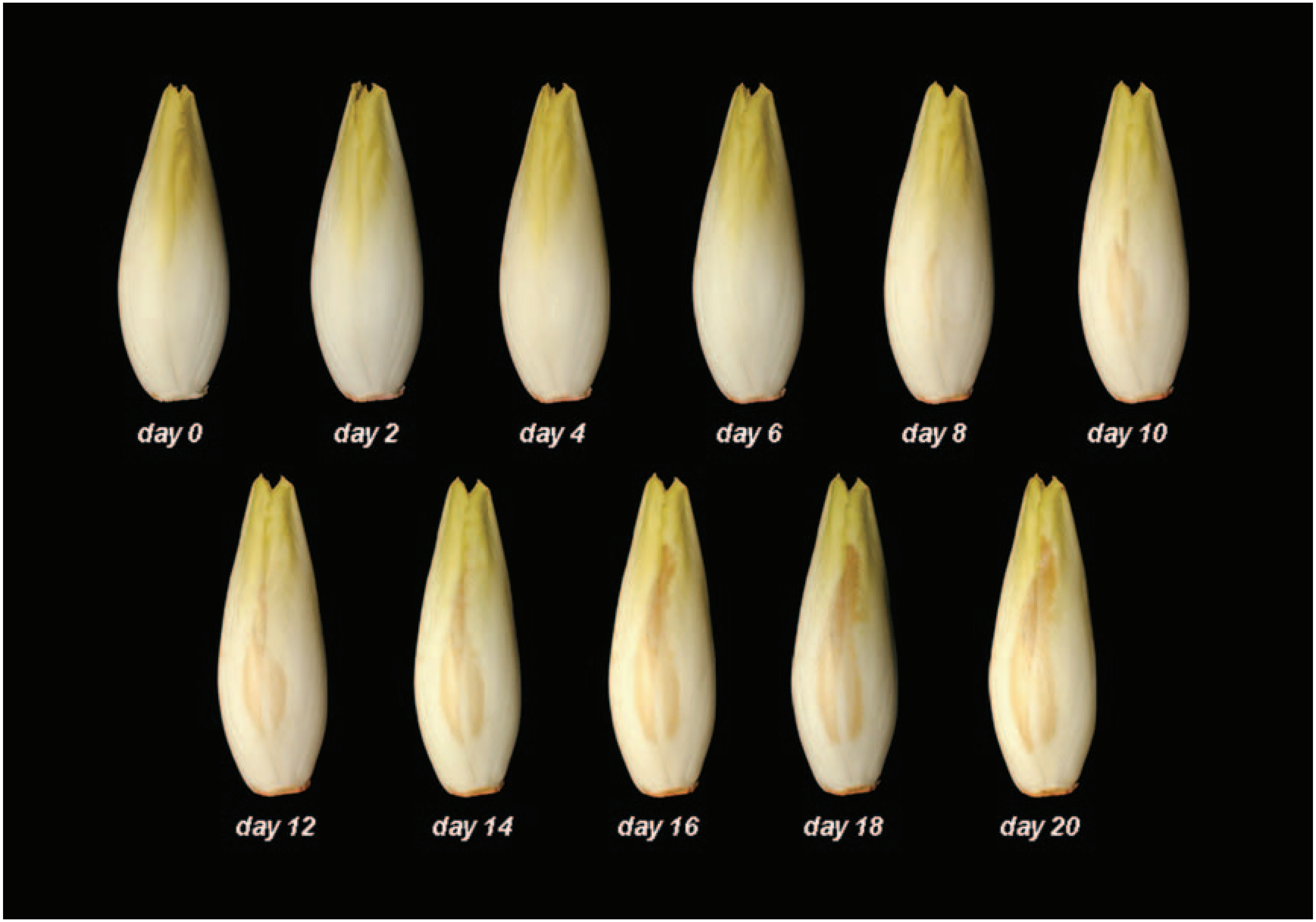
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Figure 7.13. Appearance of 'Focus' witloof chicory stored for 20 days at 10°C. After 10 days, the outer leaves start to show some signs of browning, which becomes objectionable after 12 days. Leaf opening is also evident during storage at this temperature.

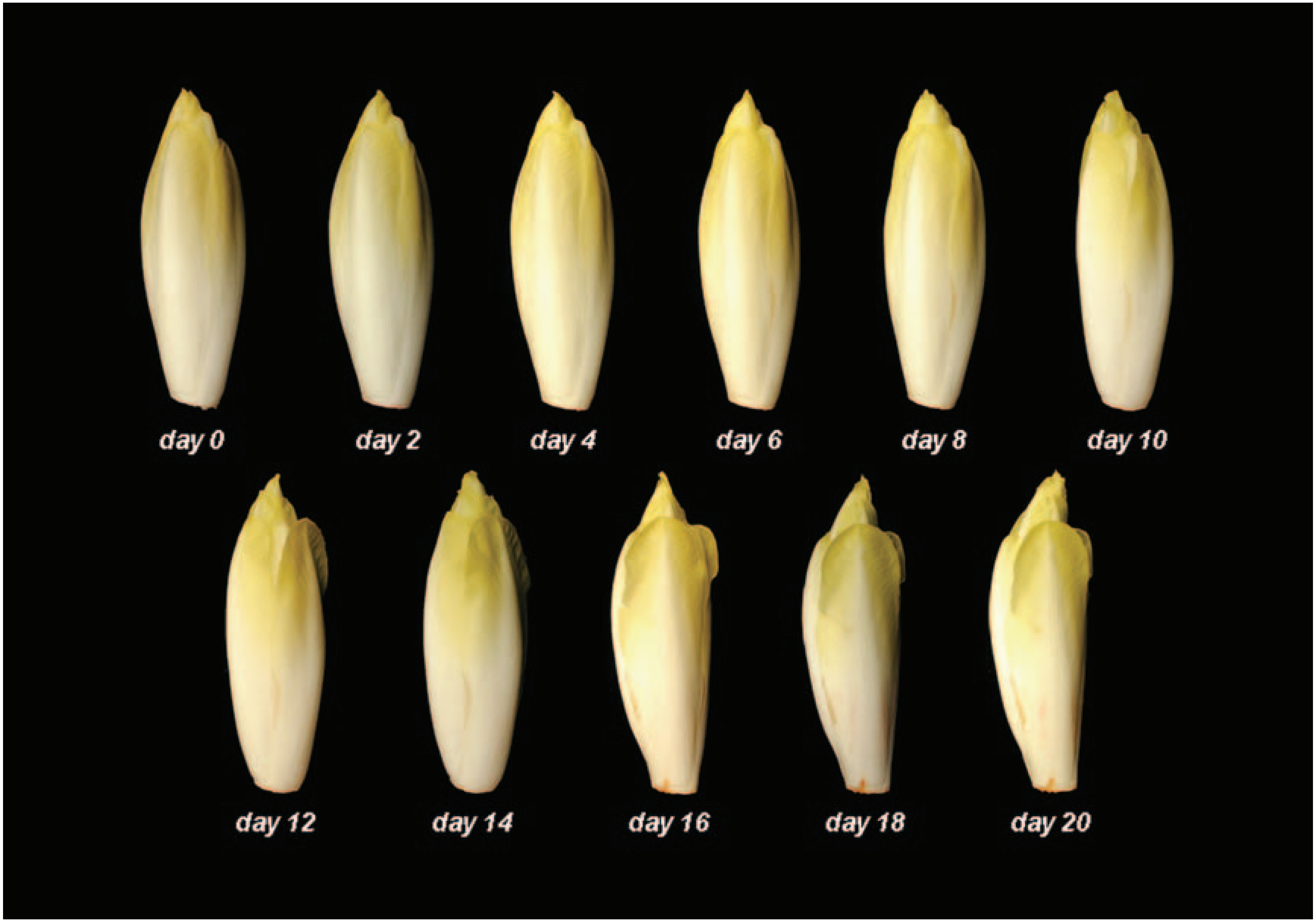
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Figure 7.14. Appearance of 'Focus' witloof chicory stored for 20 days at 15°C. After 8 days, the chicon develops an unpleasant taste and some leaf browning, and after 10 days the external leaves start to open and turn brown.

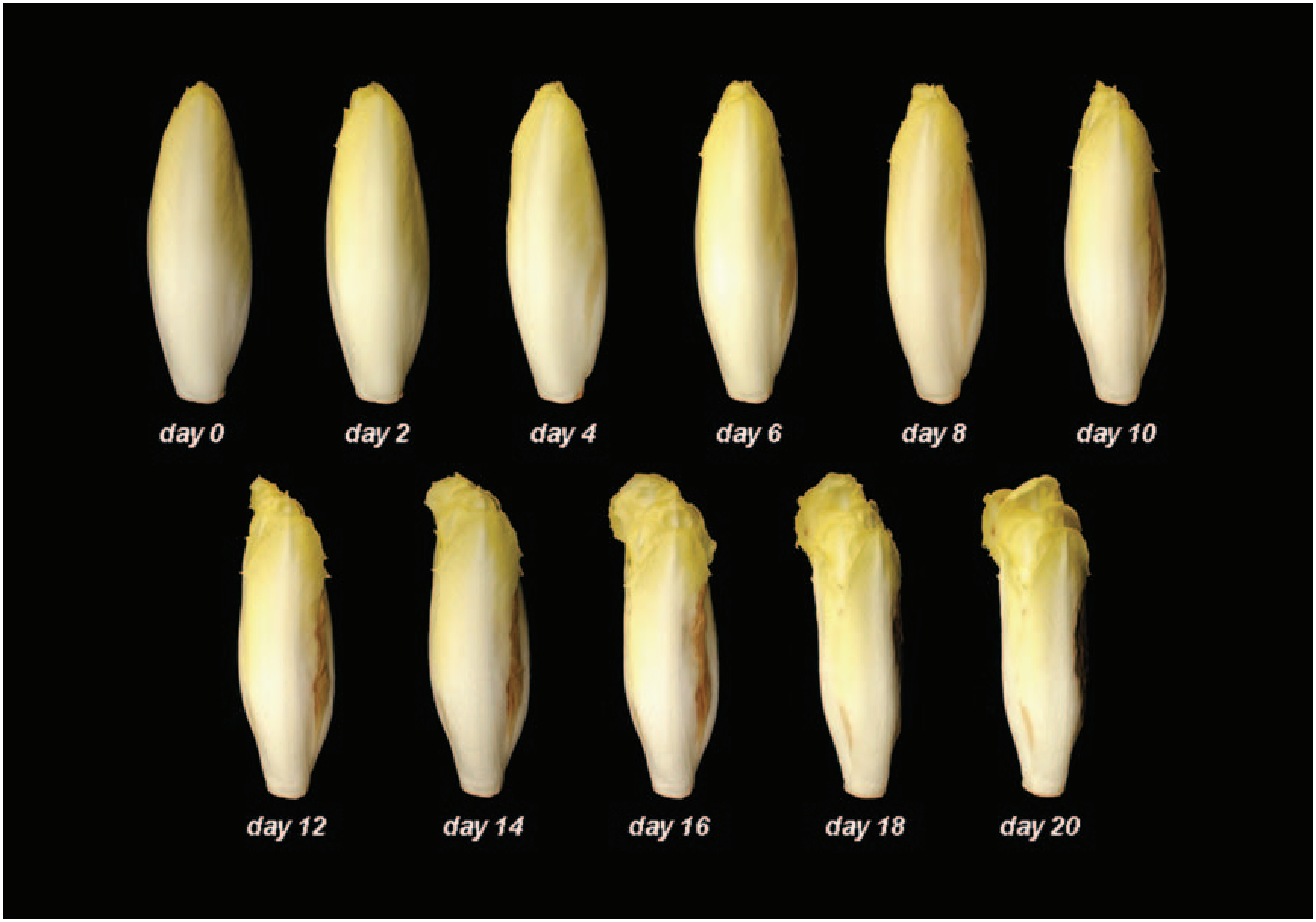
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Figure 7.15. Appearance of 'Focus' witloof chicory stored for 20 days at 20°C. After approximately 8 days, browning on the edge of the leaves starts to develop; the outer leaves start to open after 10 days; and after 20 days leaf growth is evident.

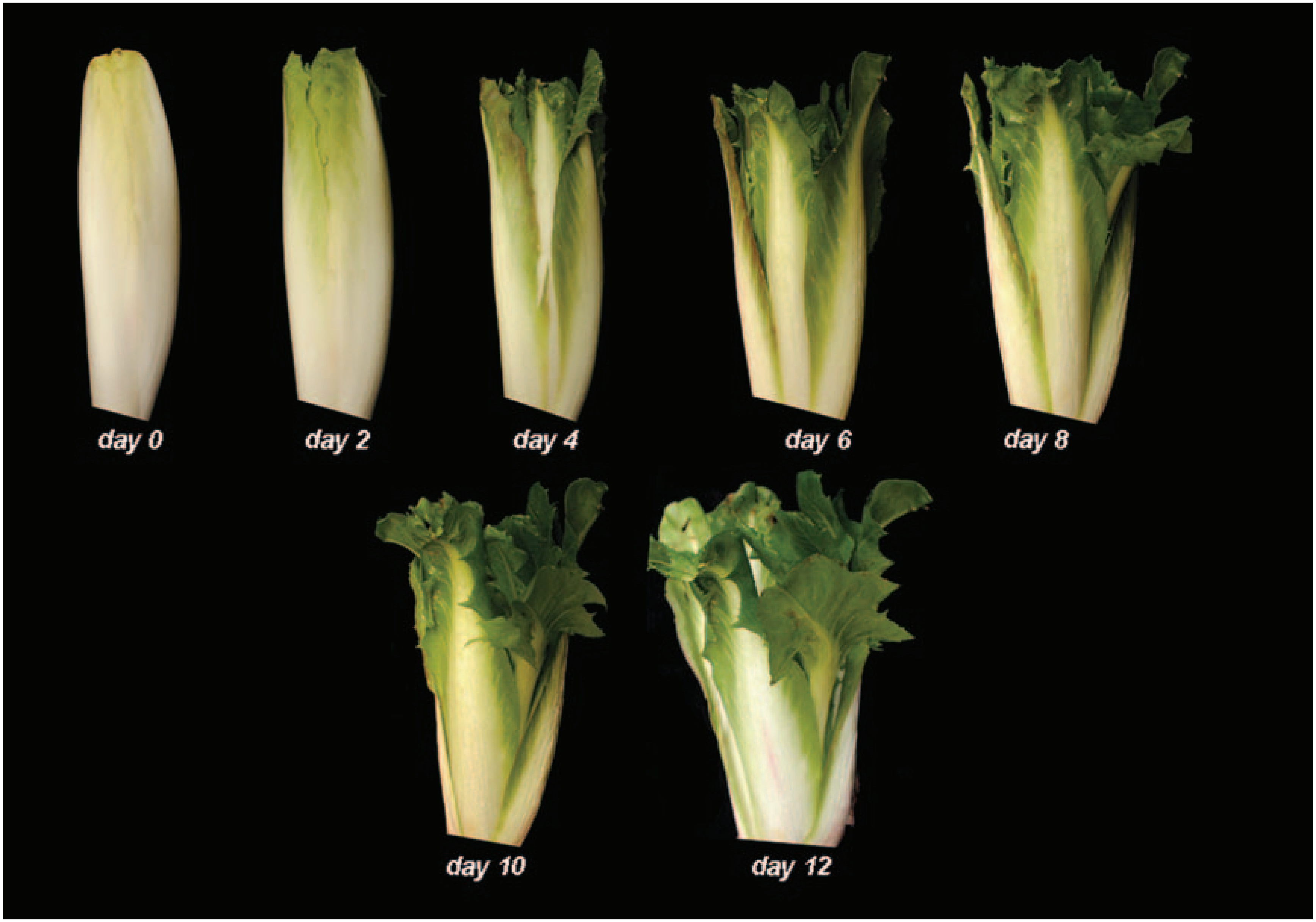

Figure 7.16. Appearance of ‘Focus’ witloof chicory exposed to fluorescent light (100 watt) for 12 days at 20°C. After 2 days chicon outer leaves start to show a light green color and some head opening, and after 12 days they are dark green and well developed. Browning also develops on the edge of the outer leaves after 4 days.

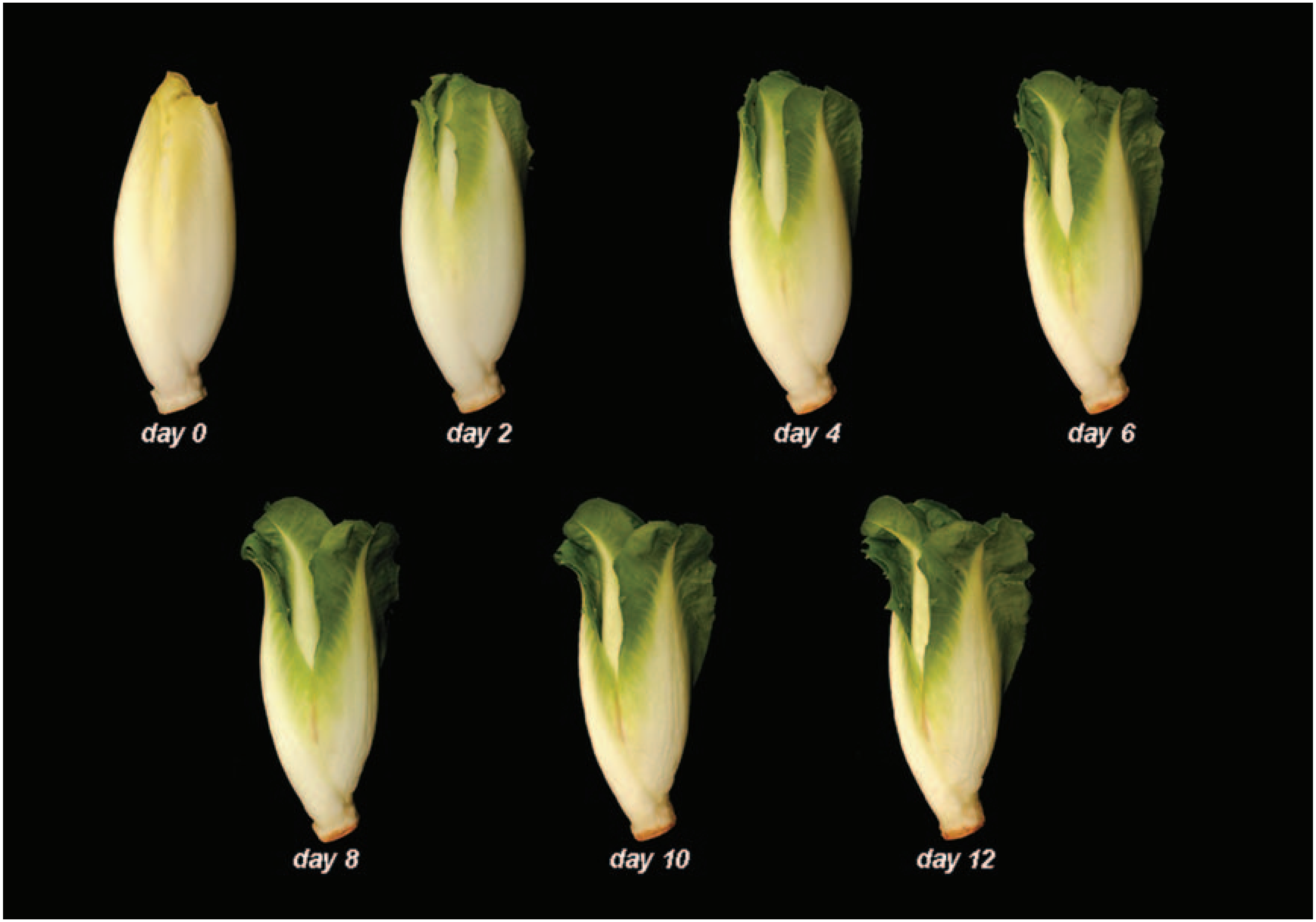

Figure 7.17. Appearance of 'Focus' witloof chicory exposed to a natural light regimen (12 hours in the dark plus 12 hours under light) for 12 days at 20°C. After 2 days chicon outer leaves start to show a light green color and some head opening, and after 12 days they are greener and well developed.

MUSHROOM

Scientific Name: *Agaricus bisporus* (Lange) Sing.
Family: Agaricus

Quality Characteristics

Agaricus bisporus, also known as the white cultivated mushroom, button mushroom, or "champignon de Paris," is the most extensively cultivated mushroom in the world, accounting for 38% of the world production of cultivated mushrooms. The major regions of cultivation are Europe, North America, and China (Adamicki 2004). The harvested portion of the mushroom consists of a round well-formed cap, the stipe or stem, the veil, and the gills. The cap protects the gills, and as it expands so the edge separates from the stem, the gills become exposed. The veil links the margins of the cap to the top of the stem, covering the immature gills. The gills are thin, vertical radiating plates located underneath the cap, and when mushrooms mature they become completely uncovered. Increased mushroom maturity is related to the growth of the stipe and gill tissue resulting in cap opening (Burton et al. 1995). Cap opening is the most remarkable characteristic observed during the postharvest development of mushrooms and is used to evaluate maturity and quality (Braaksma 2000).

Mushrooms are produced periodically in what are known as flushes or breaks, at 7–10 day intervals. Flush number is one of the factors considered to have a major influence on quality. Usually, the first break mushrooms are whiter at harvest and remain whiter in storage than the second break mushrooms, which in turn discolor more slowly than the third break mushrooms (Burton and Noble 1993).

Besides differences in the characteristics of strains, mushroom quality is influenced by many variations in the pre-harvest and postharvest environmental conditions. Within each strain, quality highly depends on the developmental stage of the fruit bodies. Gill color and opening of the cap are highly correlated with maturity and mushroom quality (Loon et al. 1995). The color of the fresh mushroom is one of the most important quality factors and is often used by the consumer to evaluate the appearance and quality of the white mushroom (Heinemann et al. 1994). Tissue discoloration (i.e., browning) is an important postharvest problem in mushrooms, as it contributes to an unappealing appearance and loss of quality. After harvest, the enzyme tyrosinase (polyphenol oxidase family) present in the mushroom is activated, and its contact with phenolic substrates leads to quinone formation. Quinones are very reactive compounds and react with themselves and other cellular compounds to form brown-colored melanin pigments, leading to tissue browning (Nerya et al. 2006; Rama et al. 2000; Smith et al. 1993). In addition to changes in color, cap opening, and stipe elongation, loss of firmness and dryness are also important indicators of mushroom quality and are greatly influenced as well by pre-harvest and postharvest environmental conditions.

Good quality mushrooms should exhibit a white color with no signs of yellowing, graying, browning, or other discoloration; should have a firm texture; should have caps well rounded and closed with a fully intact veil (i.e., no open gills); should have a smooth glossy surface; and should be of good flavor (Adamicki 2004; Burton et al. 1995; Heinemann et al. 1994). White cap mushrooms are harvested by maturity and not by size, and maturity is reached when the caps are well rounded and the veil is completely intact. Veil opening along with gill exposure are signs of aging and indicate that a mushroom is senescing and thus losing its quality. The stipe should have a small length to thickness ratio, should be straight and glossy in appearance, and should have an even cut edge (Adamicki 2004).

Overall, mushroom contains approximately 93% water, 3% carbohydrates, 2–3% proteins, 1–2% fiber, 318 mg of potassium, and 86 mg of phosphorus per 100 g fresh weight (Dikeman et al. 2005; Sapers et al. 1999; USDA 2006). Protein levels are higher in the skin of mushrooms when compared to the flesh but decrease as mushrooms mature (Burton 1988; Burton et al. 1993). Vitamin B_3 or niacin is the most abundant of all vitamins present in mushrooms, which contain 3.6 mg/100 g fresh weight (Stoller and Hall 1988; USDA 2006). Mushrooms also contain considerable amounts of total phenolic compounds, and the cap was reported to have a higher content than the stipe (Sapers et al. 1999). Likewise, the phenolic content is two to three times higher in the mushroom skin than in the flesh (Burton et al. 1993; Rajarathnam et al. 2003). The high phenolic content and polyphenol oxidase enzyme activity cause the mushroom skin to turn brown very easily when subjected to small bruises.

Optimum Postharvest Handling Conditions

Besides the quality at harvest, the use of an optimum temperature during handling and storage is crucial and determines the quality of a fresh harvested mushroom. Mushrooms should be pre-cooled promptly after harvest to a temperature between 2 and 4°C, using either hydro-cooling or forced-air cooling. Vacuum-cooling may cause increased weight loss compared to other pre-cooling methods. Besides economic factors, this weight loss may be the main reason this method is not often used to pre-cool mushrooms. Compared to conventionally pre-cooled mushrooms, vacuum-cooled mushrooms showed increased weight loss during subsequent storage at 5°C (Burton et al. 1987; Frost et al. 1989). The optimum temperature for storage of white mushrooms is 0°C (Adamicki 2004). At this temperature, storage life is expected to be 7–9 days, and 3–5 days at 2°C. High relative humidity (95–98%) is essential to prevent desiccation and loss of glossiness. Drying is correlated with blackening of the stipe and gills and curling of the cap. Mushrooms will continue to develop after harvest, which is why temperature management is extremely important. Mushrooms are easily bruised by rough handling and rapidly develop patches of brown discoloration during storage (Adamicki 2004; Rama et al. 2000).

Temperature Effects on Quality

After harvest, mushrooms lose their white color very quickly and become brown, the caps open and expose the darkening gills as spores develop, the stems lengthen, and all the tissues toughen and become rubbery (Beelman 1988). Darkening of the color or browning increases during storage, regardless of the storage temperature, but is more evident in mushrooms stored at 15 or 20°C than at 0°C (Nunes and Emond 2002b). Storage of mushrooms at 5°C maintained the browning at a constant level, with a classification of good to very good, while the browning increased for mushrooms stored at 18°C (Burton et al. 1987). Browning in white mushrooms stored at 12°C was so severe that after 3 days mushrooms were completely unacceptable for sale. Furthermore, when stored at 3°C under a temperature fluctuating regimen, browning rate was similar to that of mushrooms stored continuously at 6°C (Zhu et al. 2006). Mushroom discoloration was greatest and occurred very quickly at 18 or 20°C compared to discoloration of mushrooms stored at 5 or 0°C (Burton and Noble 1993; Murr and Morris 1975). Severity and incidence of browning is not only influenced by storage time and temperature but also aggravates if the mushroom suffers some mechanical damage like a bruise, cut, or puncture during handling. For example, browning caused by a mild 10-second bruising treatment was equivalent to the effect of 2 days of storage at 18°C, which is almost one-half of the potential shelf life of white mushrooms (Burton and Noble 1993). Furthermore, discoloration seems to be related to increased maturation, and the rate at which changes occur is affected by temperature. Mushrooms that matured faster also discolored at a faster rate (Murr and Morris 1975).

L* value of mushrooms measured on the cap decreased during storage, regardless of the storage temperature, indicating darker color, but the decrease was more significant in mushrooms stored at temperatures higher than 10°C (Nunes and Emond 2002b). Mushrooms stored at temperatures between 10 and 25°C showed a constant decrease in L* value during storage and became less white and more brown (González-Fandos et al. 2000; Kang et al. 2000; Mau et al. 1991). Mushrooms from the first flush were lighter (higher L* value) than those from the second flush (Nunes and Emond 2002b). Lopez-Briones et al. (1993) reported that mushrooms with L* values of more than 80 would be considered acceptable by consumers, while those with L* values less that 70 would be rejected. Burton and Noble (1993) suggested that a good quality, freshly picked mushroom would have L* values between 85.5 and 90, and a poor quality mushroom would have an L* value below 79.5. In fact, freshly harvested mushrooms showed L* values of 91.5 and 89 for the first and second flush, respectively (Nunes and Emond 2002b). However, L* value of the cap alone should not be used to distinguish between good and bad quality mushrooms. For example, according to L* value measurements, mushrooms from a first flush would still be considered acceptable after storage for 4 days at 20°C, but after approximately 1 day the appearance of the mushrooms was already unacceptable due to localized development of browning (Nunes and Emond 2002b). There was no significant difference between hue values of mushrooms stored at different temperatures. Chroma of mushrooms increased during storage, regardless of the storage temperature, but there was no significant difference in the chroma of mushrooms stored at different temperatures, except for those from the second flush stored at 15°C and 20°C. Increase in chroma values indicates an increase in intensity of the color, probably due to increased browning of the caps (Nunes and Emond 2002b).

Opening of the cap in harvested mushrooms is greatly influenced by the time of harvest, the initial size of the mushrooms, the storage temperature, and the humidity levels. If mushrooms are harvested early and stored for 3 days at 20°C under high relative humidity, opening of the cap may be negligible. Cap opening was observed in 50% of the mushrooms harvested 1 day before the normal harvest period and stored for 4 days at 20°C, while more than 90% of the mushrooms harvested on the normal day of harvest had open caps (Braaksma 2000). Smaller size mushrooms attained 100% cap opening after 4 days at 20°C, while larger mushrooms reached complete cap opening (100%) after 2–3 days (Braaksma et al. 1999). For mushrooms stored at 18°C, cap opening was very fast, and after 5 days the caps were well opened and the gills exposed (Smith et al. 1993). Stipe elongation often accompanies cap opening, and in mushrooms stored at 10°C stipe growth increased by about 20% after 14 days (Kang et al. 2000). For mushrooms stored at 0°C, stipe elongation was insignificant over an 8-day storage period, while at 20°C stipe growth was very fast, and an increase in length from 24 to about 30 cm between the first and second day of storage was observed (Murr and Morris 1975). Opening of the cap, elongation of the stipe, and dryness of the cap and stipe were evident after 3–7 days of storage, and after storage for 2 days at 20°C, 75% of the mushrooms showed cap opening, and after 4 days 100% of the caps were opened (Braaksma et al. 2001). Storage at temperatures lower than 20°C reduces the rate of mushroom development, but after transfer to 18°C the rate increases to a value comparable to that of mushrooms stored continuously at 18°C (Burton and Twyning 1989).

Softening and drying of the mushroom cap and stipe increased during storage regardless of the temperature, but the symptoms were more severe at higher temperatures (Nunes and Emond 2002b; Zhu et al. 2006). After 4 days at 5°C mushroom stipe and cap firmness decreased by 20 and 8%, respectively, and by 69–47% in mushroom stored at 18°C (McGarry and Burton 1994). Loss of firmness during storage of mushrooms is due to loss of water, changes in tissue morphology, and cell degradation (Burton et al. 1995). Softening of the caps and stipes during storage results from the loss of cell contents, decrease in cell turgidity, and lack of cohesion between the cells (Burton et al. 1995).

Weight loss of mushrooms significantly increased during storage, regardless of the temperature. However, weight loss was significantly higher in mushrooms stored at higher temperatures. For example, weight loss of mushrooms reached similar values for mushrooms stored for 14 days at 2°C, 8 days at 10°C, or 4 days at 18°C (approximately 18, 22, and 20% weight loss, respectively) (Burton and Twyning 1989). In another report, weight loss of mushrooms stored at 18°C attained even higher levels, and after 5 days the mushrooms had lost more than 45% of their initial weight (Burton 1988). Nunes and Emond (2002b) found weight loss to be higher in mushrooms from the first flush compared to the second flush. Thus, after 7 days at 0°C weight loss was about 20% and 16% in mushrooms from the first and second flush, respectively. In mushrooms stored at 5°C, for the same period of time, weight loss ranged from 23 to 20%, while in mushrooms stored at 10°C weight loss reached 29 and 24% in mushrooms from the first and second flush, respectively. After 7 days at 15°C, weight loss of mushrooms from the second flush attained 47%, and 57% in mushrooms stored at 20°C. First flush mushrooms were discarded after approximately 5 days at 15°C, and after 4 days at 20°C due to severe decay. Although mushrooms were packed in small polystyrene trays covered with a plastic film and maintained in an environment with 90–95% relative humidity, weight loss during storage was yet quite high (Nunes and Emond 2002b).

The values for mushroom weight loss reported in the literature are quite variable and depend on storage conditions and type of packaging. For example, mushrooms stored in stretch-wrapped polystyrene trays and at 10°C showed visual symptoms of shriveling with only 2.8% weight loss after 8 days, and after 14 days weight loss reached almost 5% (Kang et al. 2000). Other authors reported weight loss levels as low as 1.6% in packed mushrooms stored at 10°C for 11 days (Gautam et al. 1998) or 4% after approximately 5 days at 5°C (Burton et al. 1987), while others reported higher weight loss values. Weight loss of mushrooms stored at 5°C or 18°C for 7 days ranged from 25 to 35%, depending on the storage temperature and flush number (Burton and Noble 1993). In another study, weight loss from mushrooms stored at 18°C and 90–95% relative humidity was approximately 10% per day, and after 5 days mushroom initial weight was reduced by 50–60% (Smith et al. 1993). Narvaiz (1994) considered a weight loss of 14% still acceptable in mushrooms stored for 12 days at 10–12°C. In an early study, Hughes (1959) found that black stems (i.e., stipes) and open veils were correlated with the rate of water loss. However, the maximum weight loss before mushrooms were judged unacceptable varied greatly depending on the quality attribute evaluated (i.e., color, cap opening, dryness, or browning). Thus, a weight loss between 8 and 17% would correspond to a maximum acceptable discoloration (i.e., browning), or before the mushrooms were considered unacceptable for sale, while a weight loss of 24–46% would correspond to a maximum acceptable cap opening. Moreover, a weight loss of 22–42% would correspond to a maximum acceptable dryness. Since discoloration (i.e., browning) was the quality characteristic that primarily limited the postharvest life of these mushrooms regardless of the storage temperature, it should be the quality factor best related to the maximum acceptable weight loss before mushrooms became unacceptable for sale. Therefore, an average weight loss of about 12% would be considered to be the maximum acceptable amount before mushrooms became unacceptable for sale (Nunes and Emond 2002b).

Coincidentally with visual quality changes, mushrooms go through compositional changes, which are also greatly affected by the storage environment. For example, total sugar content decreases during storage of mushrooms at 5, 10, or 15°C, mainly due to a decrease in nonreducing sugars (Rai and Saxena 1989). Protein content also decreased in mushrooms stored for 5 days at 18°C, most likely due to the increase in protease activity (Burton 1988; Burton et al. 1993). Decrease in protein content observed during storage was more accentuated in mushrooms stored at 15°C than at 5 or 10°C (Rai and Saxena 1989).

Phenol content also decreased during storage of mushrooms for 5 days at 18°C (Burton et al. 1993) or during 4 days at 5, 10, or 15°C (Rai and Saxena 1989). The decrease in total phenolic content during storage is a good indicator that phenols are used as substrates for the browning reactions that occur in the mushroom tissues. Decreasing phenolic content during storage of mushrooms at temperatures higher than 0°C was attributed to an increase in polyphenol oxidase activity, which metabolizes the phenols to quinones (Rajarathnam et al. 2003). Polyphenol oxidase activity increased as the storage temperature increased, and enzyme activity doubled in mushrooms stored at 15°C compared to storage at 5 or 10°C (Rai and Saxena 1989).

Time and Temperature Effects on the Visual Quality of 'Paris' White Mushrooms

'Paris' white mushrooms shown in Figures 7.18–7.22 were harvested from a second flush with caps well formed and veil completely intact from a commercial operation in Belmont, Quebec, Canada, during the winter season (i.e., December–January). Promptly after harvest, fresh mushrooms were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Overall, discoloration or development of a brownish color of the caps, gills, and stipes is the most striking quality change during storage of white mushrooms at any temperature, and contributes to significant loss of quality. Browning develops first in the small bruises on the mushroom cap, rather than in the nonbruised areas. Browning increases with time and is more severe in mushrooms stored at higher than lower temperatures. After storage for 5–7 days at 0°C, mushrooms attain an objectionable browning, while for mushrooms stored at 15 or 20°C discoloration is objectionable shortly after approximately 1 or 2 days (Figures 7.18, 7.21, and 7.22).

Cap opening is minimum (veil slightly broken but not opened) in mushrooms stored at 0 or 5°C even after 7 days of storage (Figures 7.18 and 7.19). Mushrooms stored at 10°C show cap opening after 6 days (Figures 7.20), while those stored at 15 or 20°C show cap opening after 4 and 3 days, respectively (Figures 7.21 and 7.22). Differences in cap opening between mushrooms stored at 15 or 20°C are most likely due to differences in the humidity inside the trays, since mushrooms stored at 20°C show more severe signs of dryness and shriveling but less cap opening than those stored at 15°C. After 7 days mushrooms stored at 0 or 5°C show minor signs of softening or dryness (Figure 7.18 and 7.19). However, softening and dryness of the cap and stipe reach objectionable levels after approximately 6 days for mushrooms stored at 10°C (Figure 7.20), after 4–5 days for mushrooms stored at 15°C (Figure 7.21), and after 3 days for mushrooms stored at 20°C. Mushrooms stored at 20°C appear extremely soft, dry, and shriveled after 7 days of storage (Figure 7.22).

In summary, darkening of the color or browning, opening of the gills and stipe elongation, and dryness are the major changes in mushroom quality during storage. Changes are, however, faster and more severe as temperature increases. 'Paris' mushrooms stored at 0°C maintain a better visual quality for longer periods of time (6 days) than mushrooms stored at higher temperatures. Mushrooms stored at 5, 10, 15, and 20°C maintain acceptable visual quality during 4, 3, more than 1 day, and 1 day, respectively. After that time the visual quality of the mushroom deteriorates very quickly.

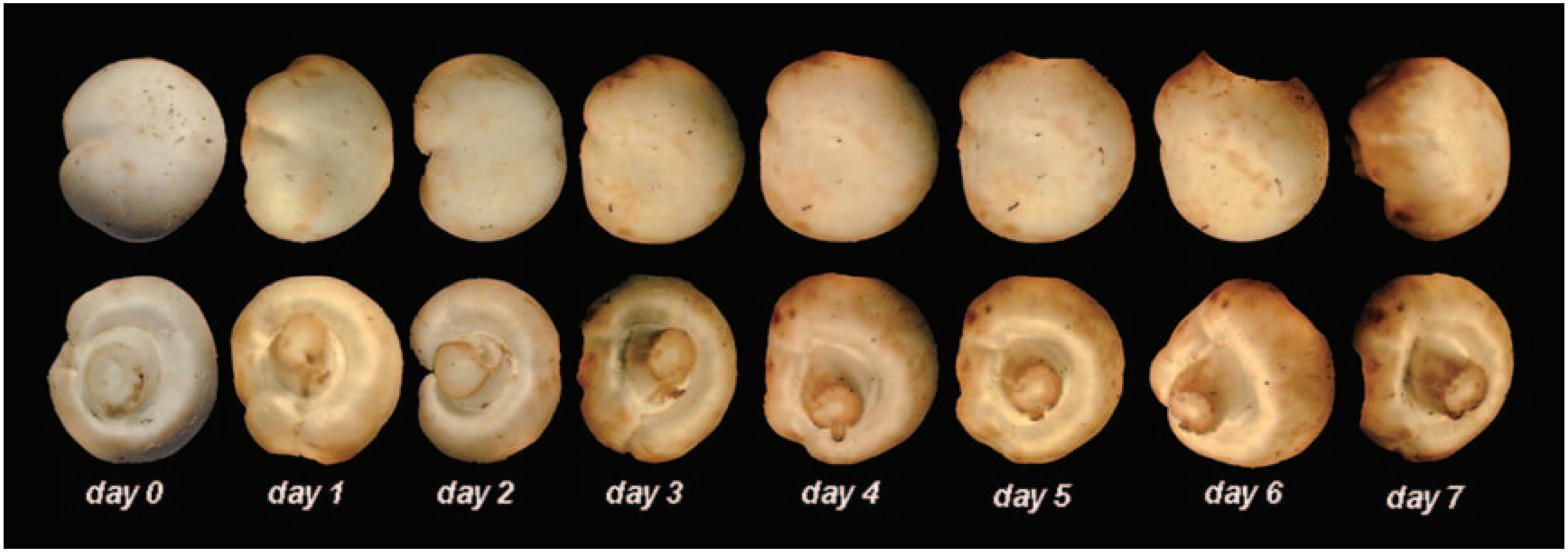
day 0
day 1
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Figure 7.18. Appearance of white mushrooms (second flush) stored for 7 days at 0°C. After approximately 3 days some surface discoloration starts to develop, and after 5–6 days darkening of the color becomes objectionable.

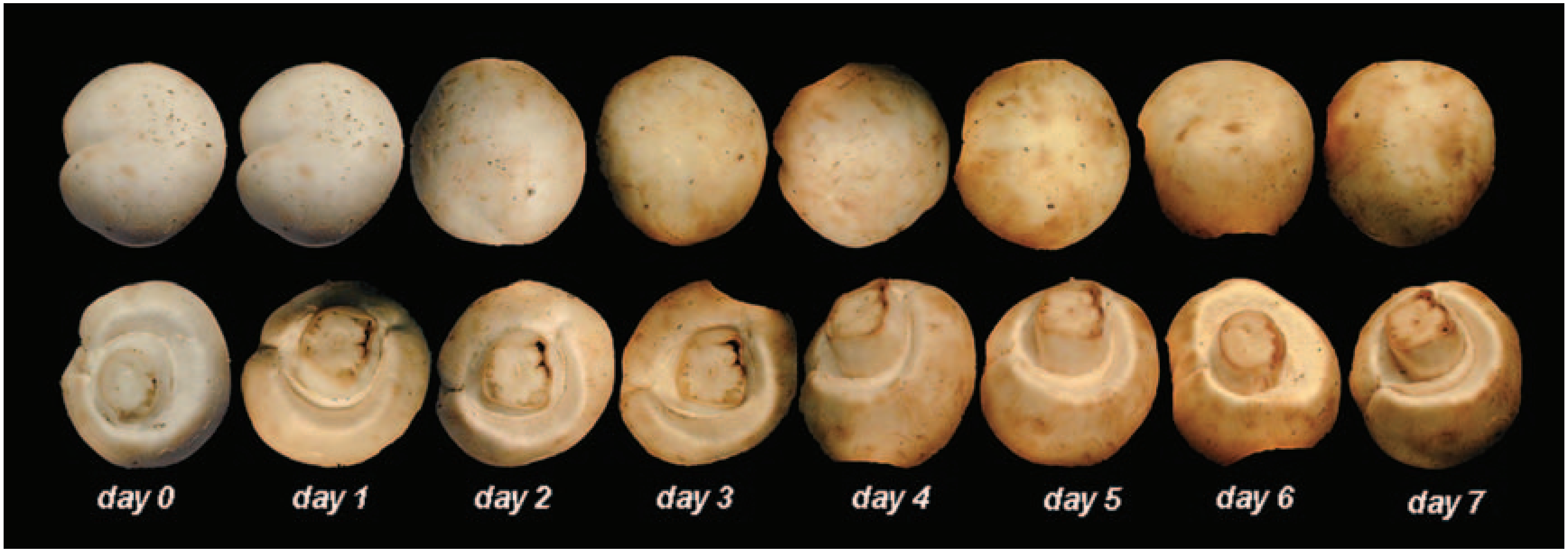
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Figure 7.19. Appearance of white mushrooms (second flush) stored for 7 days at 5°C. After approximately 3–5 days darkening of the color becomes objectionable. Cap opening is minimal (veil slightly broken but not opened) after 7 days.

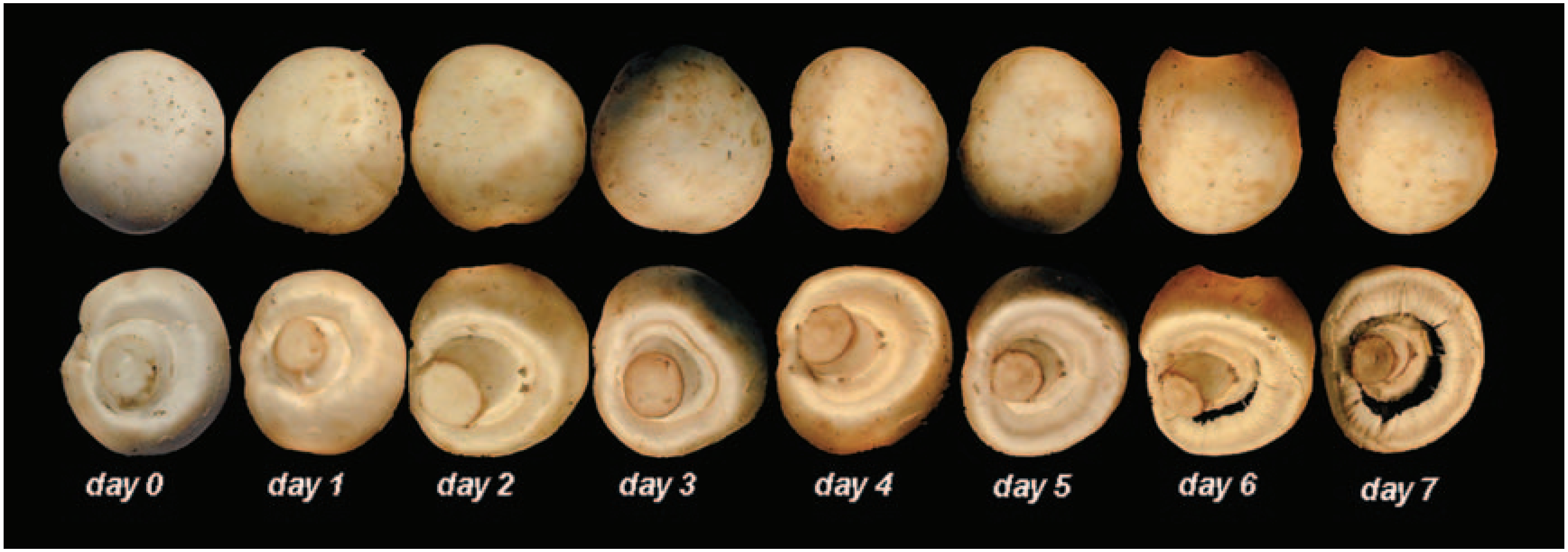
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Figure 7.20. Appearance of white mushrooms (second flush) stored for 7 days at 10°C. Darkening of the color limits the postharvest life of mushrooms to 4 days. After 6 days opening of the cap and elongation of the stipe are evident, and on day 7 the gills become exposed.

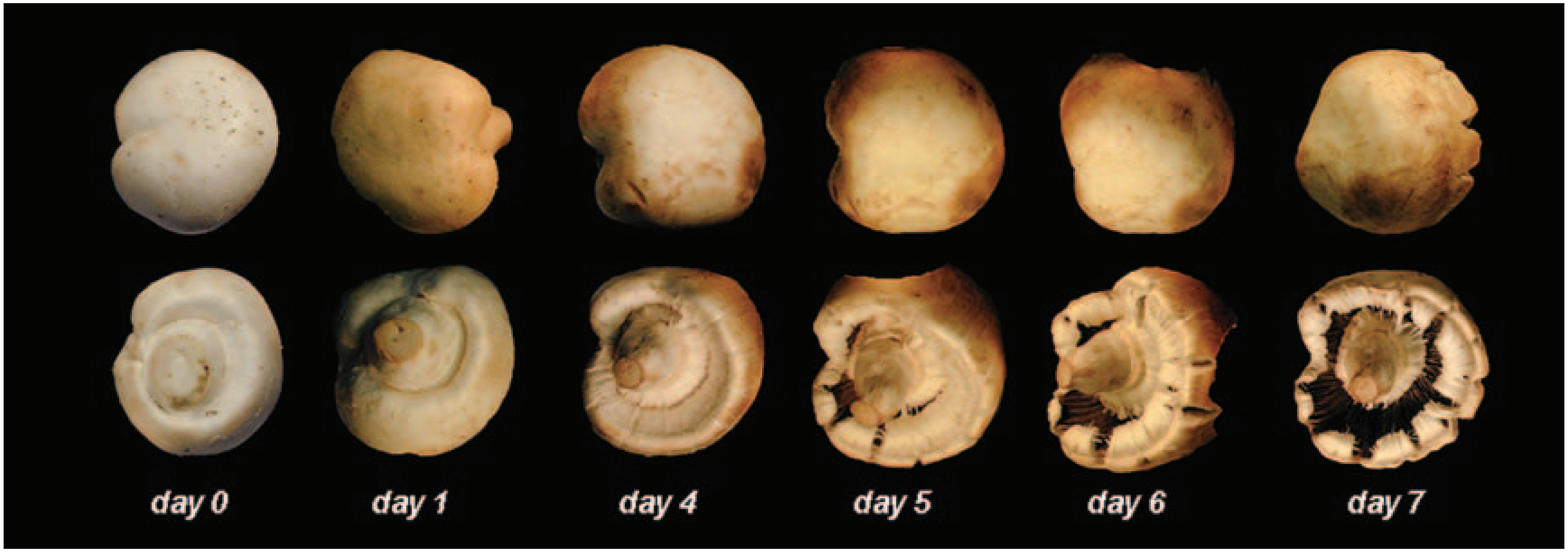

Figure 7.21. Appearance of white mushrooms (second flush) stored for 7 days at 15°C. After 1 day, darkening of color limits mushroom postharvest life, and after 4 days opening of the cap as well as elongation of the stipe starts. At day 7 the gills are completely exposed. Signs of dryness and shriveling are also evident after 4–5 days.

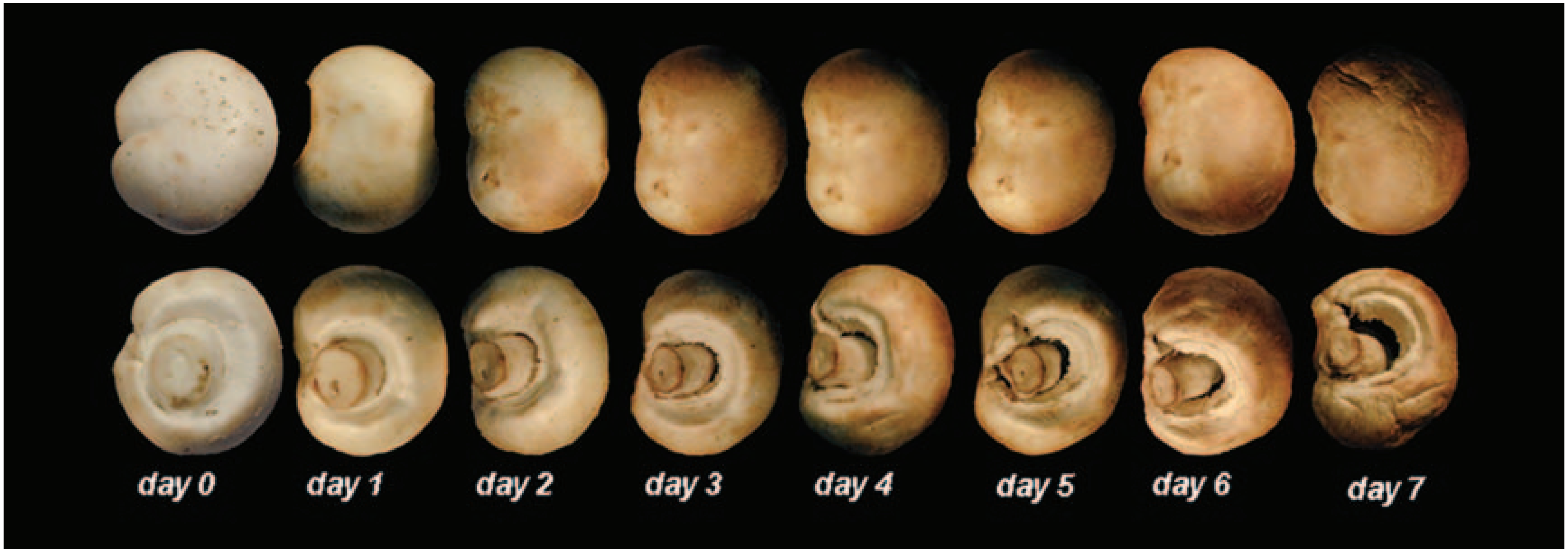
day 0
day 1
day 2
day 3
day 4
day 5
day 6
day 7

Figure 7.22. Appearance of white mushrooms (second flush) stored for 7 days at 20°C. After approximately 1–2 days, darkening of the color rends the mushrooms unmarketable. Mushrooms show unacceptable cap opening after 4 days and appear extremely dry and shriveled after 7 days.

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CHAPTER 8

ALLIUMS

Leek
Green Onion
Fresh Garlic
Bibliography

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LEEK

Scientific Name: *Allium ampeloprasum* L. Porrum group
Family: Alliaceae

Quality Characteristics

Leeks were cultivated many years ago by the ancient Egyptians, later becoming an important vegetable crop for Greeks and Romans. They were then spread throughout Europe and are now extensively cultivated in many countries, particularly in France, Belgium, and the Netherlands (De Clercq and Van Bockstaele 2002; van der Meer and Hanelt 1990). There are three main types of cultivated leeks: the European type, which has a relatively short and thick pseudostem; the Turkish type, also grown in Bulgaria and Egypt, which has a relatively long and thin pseudostem; and the Kurrat, which is grown mainly in Egypt for its leaves, as it does not produce a pronounced pseudostem (van der Meer and Hanelt 1990).

Leeks do not normally produce bulbs, and they have concentric, ensheathing leaf bases, together with folded immature leaf blades at the center, which form long edible pseudostems. Leek cultivars may vary in size and slenderness of the pseudostems (De Clerq and Van Bockstael 2002). Nevertheless, the base of a good quality leek should be white for about 3 cm, smooth and free of blemishes, and the upper part of the flat leaves should be turgid and dark green, with a whitish or bluish blossom, depending on the cultivar. The stem plate where the leaves originate must be present, and the cut bottoms should be flat (DeEll 2004; Ryall and Lipton 1979). Leeks are usually trimmed before marketing so that only a 30.5 cm portion of the green leaves remains (DeEll 2004).

The major storage tissues of leeks are the white leaf sheaths, which contain on average 83–90% water, 1.5–2% protein, 0.3% lipids, 5–14.2% carbohydrates, and 1.8% fiber. Leeks also contain vitamin A (1,667 IU/100 g fresh weight), carotenoids, such as carotene (1,000 µg/100 g fresh weight), lutein and zeaxantine (2,900 µg/100 g fresh weight), and vitamin C (12–25 mg/100 g fresh weight) in moderate amounts (USDA 2006; van der Meer and Hanelt 1990), with the leaves having higher ascorbic acid content than the stems (29 mg/100 g and 14 mg/100 g fresh weight, respectively) (Nilsson 1979). Leeks also contain flavonoids, particularly kaempferol (30 mg/kg fresh weight) (Hertog et al. 1992). The major flavor compounds of leek are sulphur-containing nonprotein amino acids, which give the leek its characteristic taste and aroma (Randle and Lancaster 2002; Schreyen et al. 1976). Leeks have a high sulfur content because of their high concentration in S-alk(en)yl cysteine sulphoxides and their metabolic intermediates (Randle and Lancaster 2002). Flavor intensity increases progressively from the outer leaf to the inner tissues, with the outer leaves containing 3.16 µmol/g fresh weight of thiosulphinate and the inner leaf tissues 5.94 µmol/g fresh weight of thiosulphinate (Freeman 1975).

Optimum Postharvest Handling Conditions

After harvest, leeks should be pre-cooled using hydrocooling, package-ice cooling, or vacuum-cooling to a temperature close to 0°C. In order to maintain best quality and reduce wilting, leeks should be subsequently stored at −1–0°C and 95–100% humidity (De Clercq and Van Bockstaele 2002; Hoftun 1978; Kurki 1971; Ryall and Lipton 1979; Suhonen 1970; van der Meer and Hanelt 1990). Overwrapping leeks with perforated plastic films is often used to prevent loss of moisture and wilting (Hruschka 1978; Ryall and Lipton 1979). Under such conditions leeks can be stored for 2–3 months (Fenwick and Hanley 1985; Ryall and Lipton 1979). Exposure to 4 or 10°C will reduce the postharvest life of wrapped leeks to about 2 weeks to 1 week, respectively, while quality of leeks stored at 21°C will deteriorate within 3–6 days (Hruschka 1978). Yellowing of the leaves, wilting, and decay are important limiting quality factors during storage (van der Meer and Hanelt 1990). When stored at temperatures higher than 5°C, elongation and curvature of the leaves may also occur (Anonymous 2002b; DeEll 2004; Hruschka 1978; Tsouvaltzis et al. 2006b). Exposure to exogenous ethylene may result in accelerated softening, yellowing of the leaves, and increased decay (DeEll 2004).

Temperature Effects on Quality

The major postharvest symptoms of leek quality deterioration are wilting, yellowing of the leaves, inner leaf growth, and curvature (Hruschka 1978). In general, the white part of the leek deteriorates at a slower rate than the green leaves. The green leaves wilt easily, turn yellow, and decay during storage, while the white part of the leek is relatively resistant to disease and usually deteriorates after the leaves have decayed (Goffings and Herregods 1989; Suhonen 1970). Inner leaf growth was also observed during postharvest storage of leeks and was highly correlated with storage temperature (Hruschka 1978; Tsouvaltzis et al. 2006b). When stored at 0°C leek leaf growth increased at a rate of 0.31–0.6 mm/day, depending on the size of the stalk, while in leeks stored at 10°C growth rate was about 2.7–4.9 mm/day (Tsouvaltzis et al. 2006b). After 9 days, a maximum inner leaf growth of 7.5 mm was observed in leeks stored at 4°C (Tsouvaltzis et al. 2006a). Removal of the base of the leek stalk that contains the meristem and additional pre-storage hot-water treatments between 50 and 57.5°C for about 60-10 minutes, respectively, considerably reduced leaf growth, yet increased moisture and total thiosulfinate losses during subsequent storage (Tsouvaltzis et al. 2006a, 2006b, 2007).

During prolonged storage of leeks at −1.5°C–2°C, moisture loss may be considerably high (15–50%), regardless of the relative humidity of the surrounding environment (Gariepy et al. 1984, 1994; Suhonen 1970). Weight loss ranged from 0.77 to 2.43% in leeks stored for 30 days at −2°C, while in leeks stored at −1°C or 0°C weight loss ranged from 1.21 to 4.10% (Hoftun 1978). Weight loss of leeks stored at −1°C and 75% relative humidity reached 19% after 5 months, while in leeks stored at 0°C and 95–100% relative humidity weight loss was 11% of the initial leek weight (Kurki 1979). On the other hand, a maximum weight loss of about 37% was observed in leeks after only 8 weeks of storage at 0°C and 94–96% relative humidity (Goffings and Herregods 1989). In addition, in leeks stored at 1.5°C and 80% relative humidity a maximum weight loss of about 50% was observed after about 5 months (Gariepy et al. 1984, 1994). After only 3 days of storage at 7°C, weight loss of leeks was about 0.5%, whereas leeks stored at ambient temperature lost about 45% of their initial weight after 3 days (Takama and Saito 1974). Moderate wilting was noted when leeks lost about 15% of their weight after harvest (Anonymous 2002b), yet leeks were considered unacceptable for sale at a maximum weight loss of 7% (Robinson et al. 1975).

Besides the losses in the weight due to water loss, which often constitutes more than one-half of the total storage losses, losses due to trimming also contribute to the total weight loss of leeks during storage (Gariepey et al. 1994; Hoftun 1978; Kurki 1971). For example, when stored at 0°C for 30 days, trimming losses were about 11.1%; however, losses increased to 48.5% in leeks stored at 12.5°C (Hoftun 1978). After 150 days of storage at 1.5°C and 80% relative humidity, trimming losses in leeks ranged from 29.9% to 43.8%, with total storage losses in some cultivars higher than 80%. Similarly, during prolonged storage of leeks at temperatures ranging from −1.5°C to 0°C, total losses (i.e., weight and trimming losses) were in some cases as high as 80% (Hoftun 1978).

Total ascorbic acid, sugar, carotene, and chlorophyll contents of leeks decreased as storage time and temperature increased (Kurki 1979; Takama and Saito 1974). After 4 months at −1°C, initial vitamin C content of leeks decreased by about 46%, while in leeks stored at 0°C the decrease was about 30% (Kurki 1979). Decrease in the initial reducing sugar content was about 22 and 30% in leeks stored at −1°C or at 0°C, respectively. Initial chlorophyll and carotene contents of leeks also decreased during storage by about 73 and 79%, respectively, after 4 months of storage at −1°C or 0°C (Kurki 1979). In leeks stored at 7°C, initial carotene content was reduced from 13.93 to 5.16 mg/100 g fresh weight after only 2 days, which corresponded to a decrease of about 63% on the initial carotene content, while in leeks stored at ambient temperature initial carotene content was reduced to 5.38 mg/100 g fresh weight (Takama and Saito 1974).

Time and Temperature Effects on the Visual Quality of 'Titan' Leeks

'Titan' leeks shown in Figures 8.1–8.5 were harvested at the mature stage with about 2.5 cm in base diameter, from a commercial operation on the Orleans Island, Quebec, Canada, during the fall season (i.e., September). Promptly after harvest, fresh leeks were stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

During storage, visual quality deterioration of leek leaves occurs much faster than pseudostem deterioration, due mostly to yellowing and wilting. Inner leaf elongation is probably the most remarkable visual change that occurs during storage of leeks and is greatly influenced by the storage temperature. The pseudostem of 'Titan' leeks stored at 0°C maintains acceptable visual quality during 22 days (Figure 8.1). However, after 14 days inner leaf elongation is evident. The color of the leaves also changes from a darker green to a yellowish-green after 22 days, and wilting is evident in some of the external green leaves. At this time, trimming may be necessary for marketing purposes. The inner leaves continue to grow as storage progresses, and after 28 days, the inner leaves are completely separated from the external leaves, whereas the external leaves appear less green, more yellowish, and wilted compared to at harvest.

Inner leaf elongation is much faster in leeks stored at 5°C than at 0°C, and after only 5 days the inner leaves start to grow and separate from the external leaves (Figure 8.2). Yellowing and wilting of the leaves becomes apparent after 12 days, and after 20 days, the leaves are completely deteriorated due to yellowing, wilting, and dryness, whereas the inner leaves have grown and separated from the external leaves. The pseudostem maintains acceptable visual quality during 20 days, but after 14 days the base where the remaining roots are still attached appears drier and slightly brown.

'Titan' leeks stored at 10°C maintain acceptable visual quality during 7 days, yet at this time inner leaf elongation is already extraordinary (Figure 8.3). The inner leaves continue to develop as storage progresses, and after 12 days, they are extremely developed and completely separated from the external leaves. The pseudostem maintains acceptable visual quality during 12 days, yet the external white leaves appear discolored at the transition point between the white part of the leek and the leaf incipience.

Visual quality deterioration of the outer leaves is very quick when ‘Titan’ leeks are stored at 15°C (Figure 8.4). After 10 days, the color of the external leaves changes from a bright green to a yellowish-green, and the leaves also appear dry and wilted. Simultaneously, the inner leaves continue to grow throughout storage. The pseudostem maintains acceptable visual quality during 10 days, yet the external layer appears drier and less white than at harvest.

‘Titan’ leek deterioration is extremely quick at 20°C, particularly for the green leaves (Figure 8.5). After only 4 days, the leaves are extremely dry, wilted, and yellowish, while inner leaf elongation is also evident. After 7 days, leaf and pseudostem quality is very poor due to yellowing and dryness, and at this time leeks would not be acceptable for marketing purposes even with extensive trimming.

Overall, visual quality of ‘Titan’ leeks is better retained if stored at 0°C. At this temperature, leaf and pseudostem quality remain acceptable for 22 days, yet some trimming would have been necessary for marketing purposes. Storage at 5°C reduced the postharvest life of leeks to 12 days, at which time some trimming would have been necessary. ‘Titan’ leeks stored at 10 and 15°C retain acceptable visual quality during 7 and 5 days, respectively, whereas visual quality of leeks stored at 20°C is no longer acceptable after 4 days.

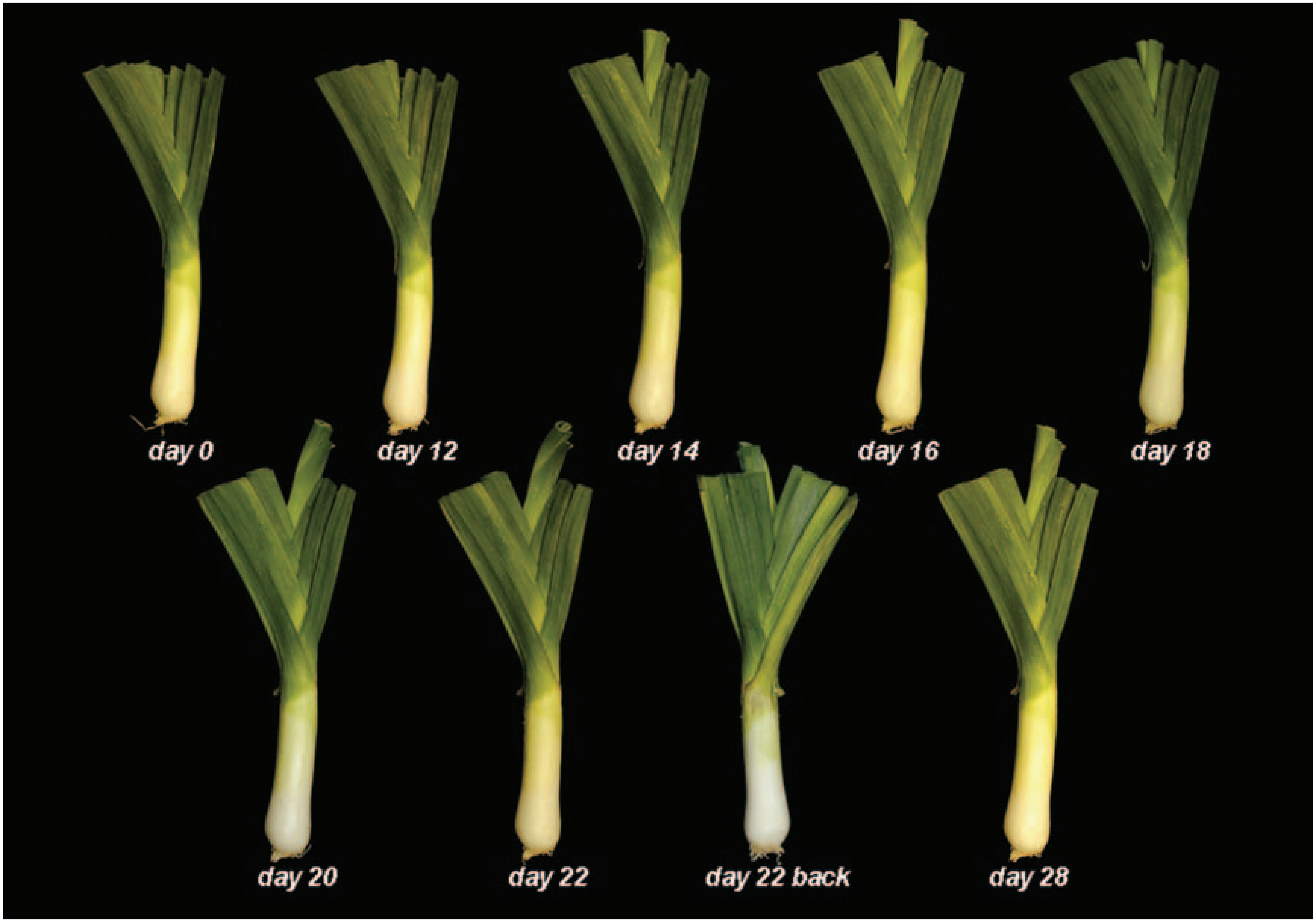
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Figure 8.1. Appearance of 'Titan' leek stored for 28 days at 0°C. Leeks maintain acceptable visual quality during 22 days, but after 14 days inner leaf growth is evident.

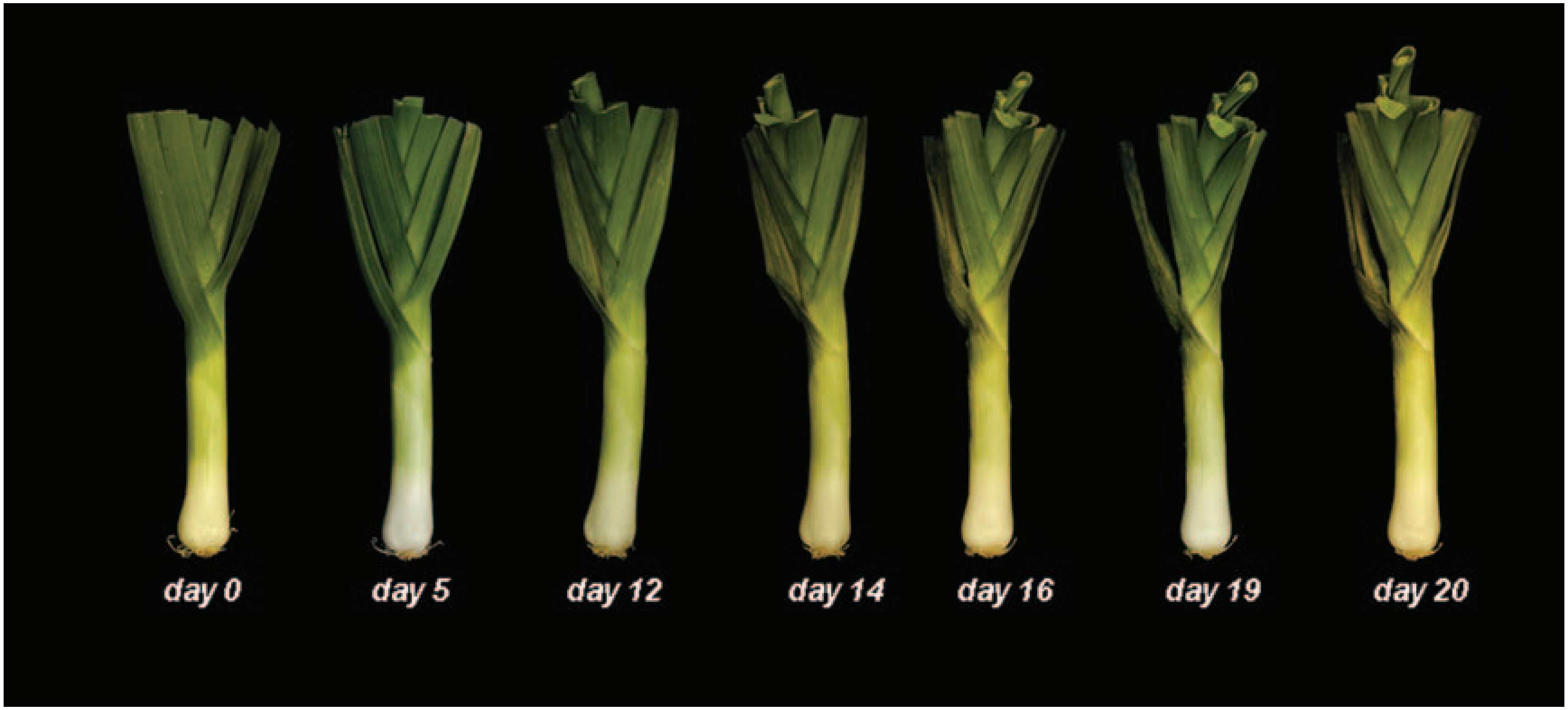
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Figure 8.2. Appearance of 'Titan' leek stored for 20 days at 5°C. Leeks maintain acceptable visual quality during 12 days; however, leaf elongation is evident after 5 days.

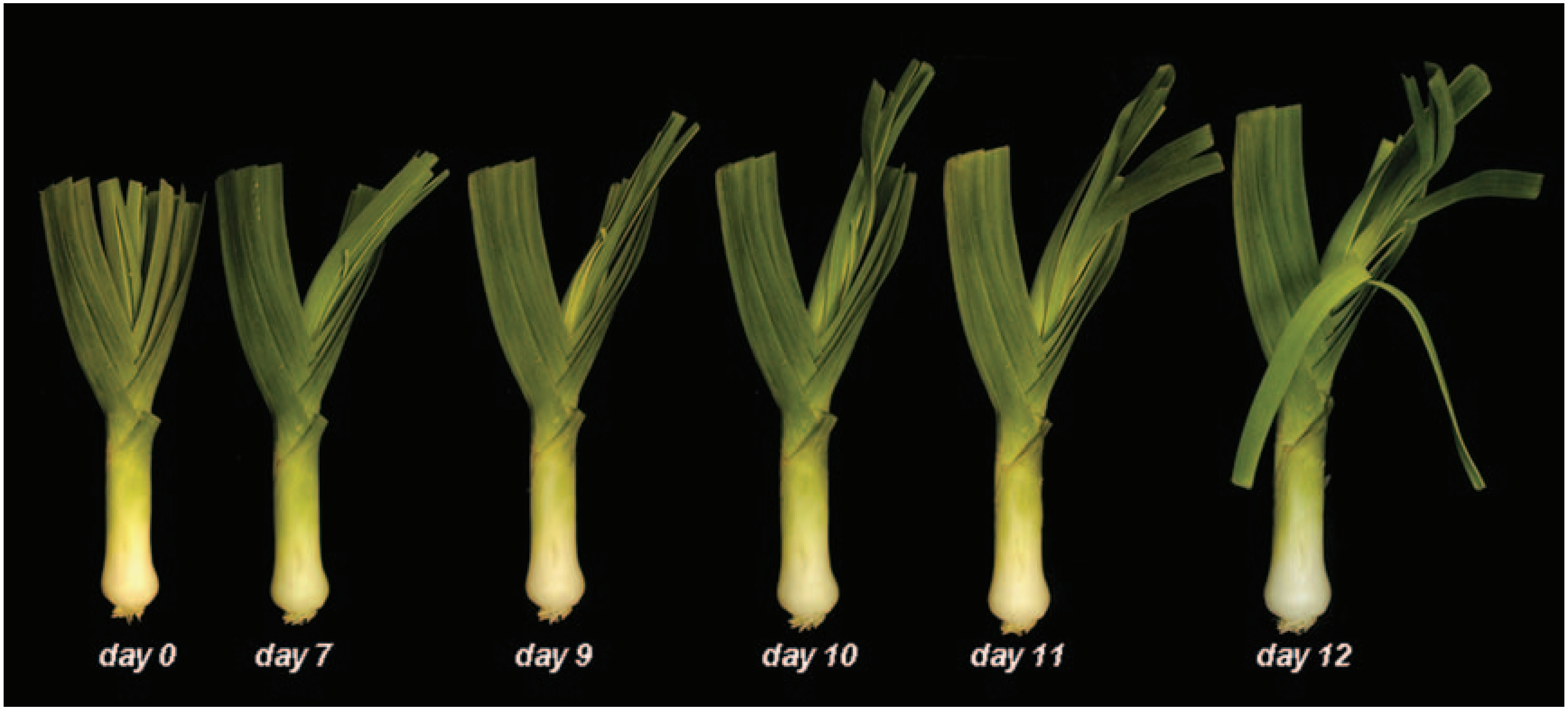
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Figure 8.3. Appearance of 'Titan' leek stored for 12 days at 10°C. Leeks maintain acceptable visual quality during 7 days. Inner leaves are extremely developed after 12 days.

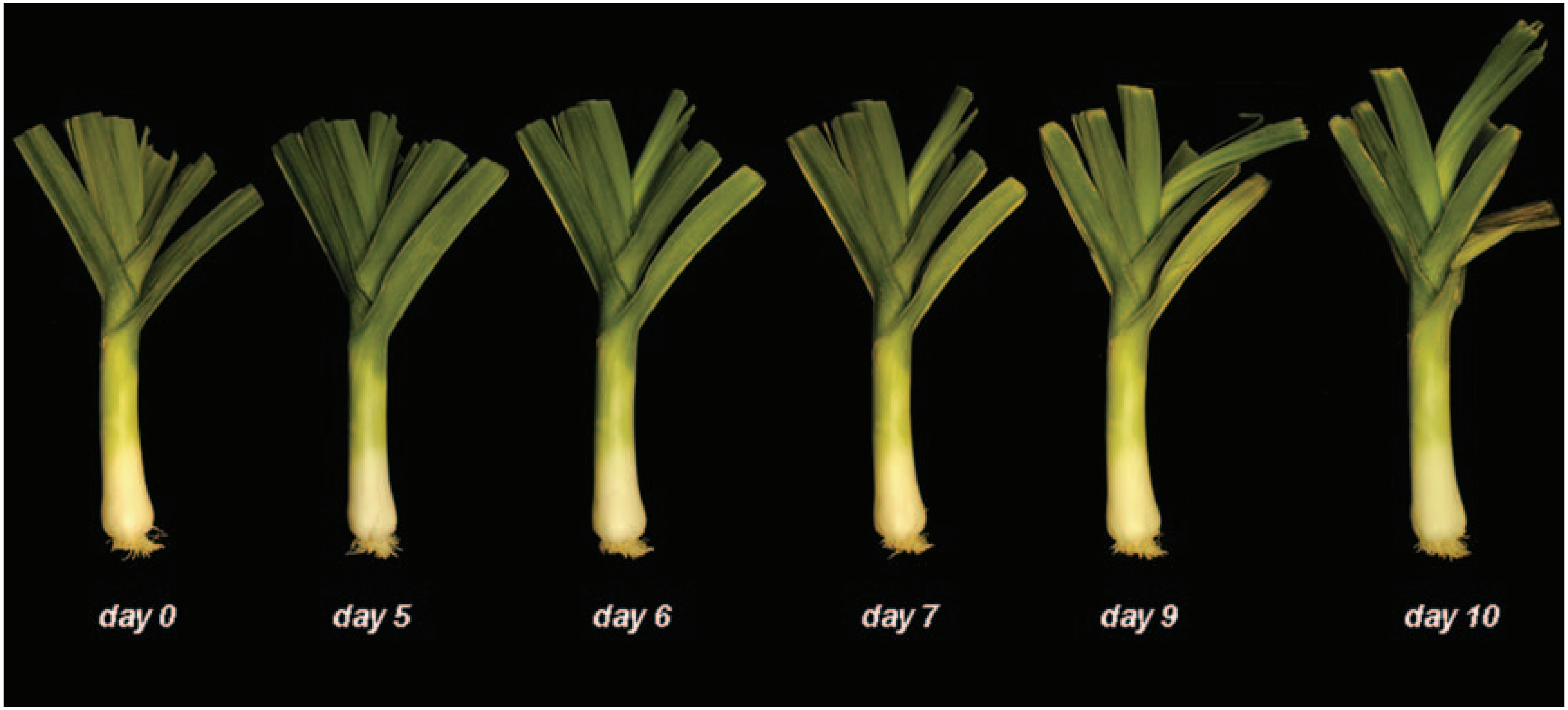
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Figure 8.4. Appearance of 'Titan' leek stored for 10 days at 15°C. Leeks maintain acceptable visual quality during 5 days. After 6 days inner leaf elongation is evident.

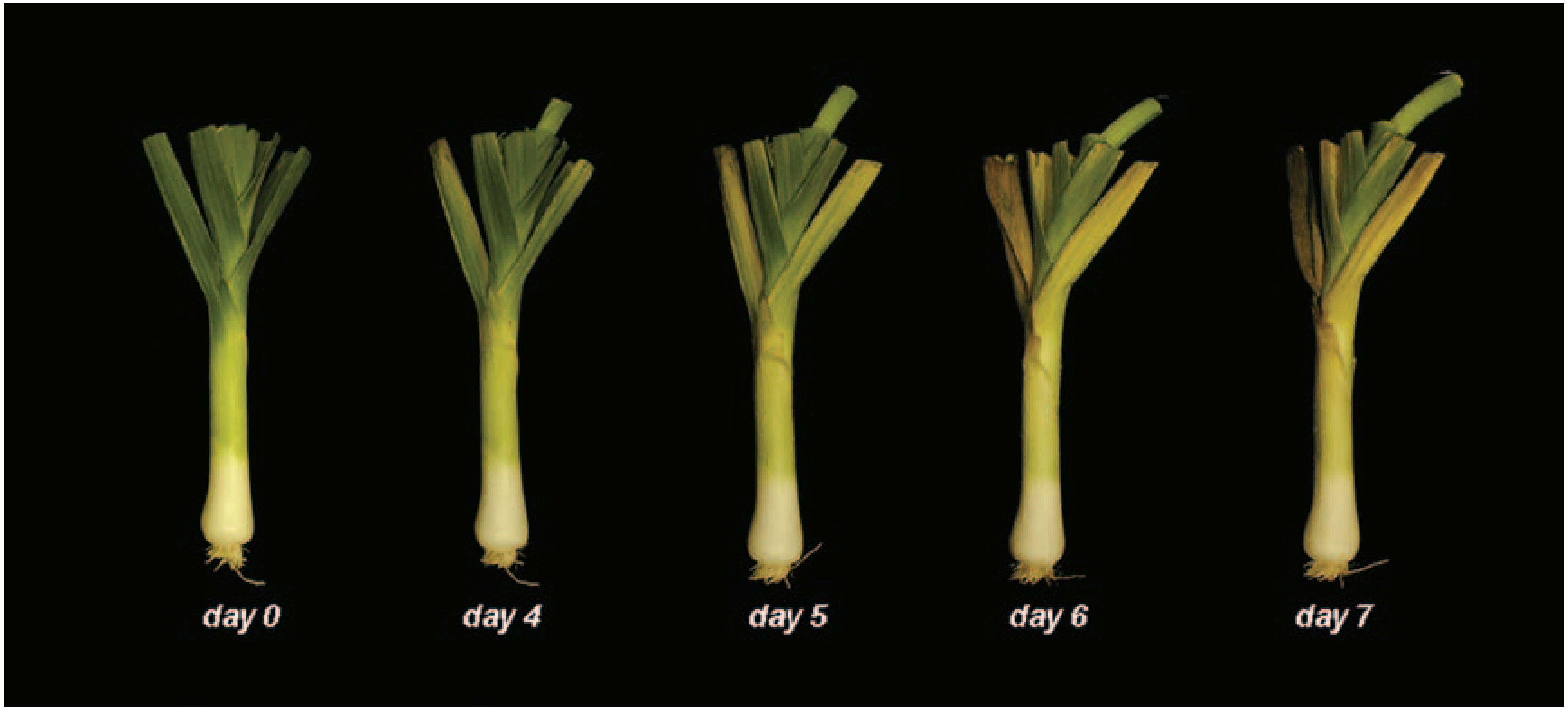

Figure 8.5. Appearance of ‘Titan’ leek stored for 7 days at 20°C. After 4 days inner leaf elongation is evident, and after 7 days leeks appear completely deteriorated.

GREEN ONION

Scientific Name: *Allium cepa* L.
Family: Alliaceae

Quality Characteristics

Onions are cool-season plants grown in temperate regions to harvest as green shoots (i.e., green onions) for salad use or to harvest as mature bulbs. Green onions are generally bulbing-type white cultivars that are thickly planted and harvested at the miniature bulbing stage and sold bunched. There are, however, other onion cultivars specially bred for bunching (*Allium fistulosum*) that do not bulb (Anonymous 2002a; Ells 2007; Voss and Mayberry 1999). The different species (i.e, *Allium cepa* or *Allium fistulosum*) can be identified by the shape of the bottom of the green leaves, near the area where they turn white. The leaf cross section of *Allium cepa* has a flat side or is D-shaped, whereas *Allium fistulosum* is round or O-shaped (Anonymous 2002a). Green onions are sometimes called scallions, which is the name given to immature bulbing onions. Scallions have thick necks and do not store well, and for that reason they are often sold bunched (Boyhan et al. 1999; Ells 2007).

Green onions for bunching can be harvested from pencil size until they have attained suitable bulb size (usually from about 0.6–1.3 cm in diameter at the base plate of the immature bulb), with at least 5–7.5 cm of white stem, and with green foliage. Green tops are usually trimmed to about 30 cm before marketing (Anonymous 2002a; Adamicki 2004; Suslow and Cantwell 2007). High-quality green onions must be well formed, thin necked, turgid, crisp, bright in color, and free of any discoloration (Ryall and Lipton 1979; Suslow and Cantwell 2007). The roots should be trimmed close to the base, but the base should not be cut or injured. Bunched onions should be tied only tightly enough to hold the stalks together without breaking them (Ryall and Lipton 1979).

Green onions (including tops and bulb) contain on average 90% water, 1.8% protein, 0.2% lipids, 7.3% carbohydrates, 2.6% fiber, and 2.3 g of total sugars per 100 g fresh weight (USDA 2006). Green onions also contain about 4.5–46 mg of ascorbic acid (vitamin C)/100 g fresh weight, 997 IU vitamin A/100 g fresh weight, 150–598 μg of β-carotene, and 1,137 μg of lutein plus zeaxanthin/100 g fresh weight (Bushway et al. 1986; Chen et al. 1993; Floyd and Fraps 1939; Tomasevic and Naumovic 1974; USDA 2006). They also contain phenolic compounds (30 mg of total phenolic compounds/100 g fresh weight), namely kaempferol (5 mg/100 g fresh edible part), which was identified as the major flavonoid compound in green onions (Huang et al. 2007).

The pungent flavor of green onions results from certain sulfur volatiles that are released through the hydrolysis of flavor precursors, S-alk(en)yl-L-cysteine sulfoxides, by action of the enzyme alliinase once the tissues are damaged (Lancaster and Kelly 1983; Lancaster et al. 1984). The leaves of bunching onions contain about 1.73 mg of total sulfoxides/g fresh weight (Yoo and Pike 1998) that together with other antioxidants, such as phenolic compounds and vitamin C, confer relatively good free-radical scavenging capacity and antioxidant properties to green onions (Benkeblia 2005). In general, the levels of sulfur compounds increase from the green to mature stage as onions develop (Lancaster et al. 1984).

Optimum Postharvest Handling Conditions

Green onions should be pre-cooled within 4–6 hours after harvest to a temperature below 4°C by using hydro-cooling, forced-air cooling, or vacuum-cooling. Crushed ice over the onions (top-icing) may be used to maintain the temperature and moisture content during handling and distribution. If vacuum-cooled, green onions should first be wetted and then placed in individual perforated plastic bags, to avoid excessive moisture loss during cooling (Hruschka 1974; Ryall and Lipton 1979). Onions should be subsequently stored at 0°C and 95–98% relative humidity. If handled under such conditions, green onions should maintain excellent appearance during 3–4 weeks. If held at 5°C, green onions will retain good quality during only 1 week. At higher temperatures rapid yellowing, decay, and slimy appearance of the leaves will develop (Adamicki 2004; Boyhan et al. 1999; Hruschka 1974). Upward bending of young, elongating shoots may occur in horizontally packed green onions (Hruschka 1971; Suslow and Cantwell 2007).

Temperature Effects on Quality

Green onions are highly perishable, and their postharvest life can be greatly reduced if they are handled under inadequate conditions. For example, postharvest life of freshly harvested green onions stored at 10°C was reduced to 7 days due to general deterioration, discoloration of the outer oldest leaf, and leaf curvature, whereas after 21 days at 0°C green onions still had a high visual quality and leaf curvature was absent. Postharvest life of green onions stored at 5°C was limited to about 2 weeks (Hong et al. 2000). Postharvest continuous growth, leaf deterioration, and visible pathogen infection developed faster in green onions stored at 18°C than in onions stored at 2°C. Green onions maintained a fresh appearance without any major deterioration in the visual quality during 1 week when stored at 2°C, yet after only 2 days at 18°C visual quality of green onions became unacceptable (Atta-Aly 1998). Similarly, after 2 days at 0 or 4°C bunched onions were fresh, green, and without any signs of sprouting, whereas after 2 days at 10°C they appeared less fresh, the bases were slightly slimy, and 10% of the onions were sprouted. When stored at 16 and 21°C 100% of the green onions had sprouted and appeared moderately to severely slimy (Hruschka 1971). After 4 days at 21°C onion length increased by 54%, whereas onions stored for the same period of time at 0 or 4°C elongated only 2.2–4.8%, respectively (Hruschka 1971, 1974). Furthermore, decay developed in 55–100% of the green onions after 3 days at 10°C plus 2 additional days at 21°C, while no decay was noticeable in green onions stored for 3 days at 0°C plus 2 additional days at 21°C (Hruschka 1971).

Wrapping green onions in plastic film helped reduce weight loss and delay loss of freshness and turgidity, resulting in a better appearance compared to unwrapped onions (Hruschka 1971, 1974). For example, while weight loss in wrapped green onions was about 1% after 3 days at 0, 4, or 10°C, in unwrapped green onions weight loss attained 11, 12, and 18%, respectively, after the same period of time. Loss of turgidity and wilting became evident when weight loss attained 15%, and at 20% weight loss, turgidity and wilting of green onions became objectionable. At 34% weight loss green onions were severely dried and stiff (Hruschka 1971, 1974).

Total soluble sugars increased during storage of green onions from 58.6 g/kg fresh weight after 7 days to 70.2 g/kg fresh weight after 14 days of storage at 5°C, while total thiosulfinate content remained unchangeable from day 7 to day 14 (1.43 mmol/kg fresh weight) (Hong et al. 2000).

Time and Temperature Effects on the Visual Quality of 'Southport White Globe' Green Onions

'Southport White Globe' green onions shown in Figures 8.6–8.10 were harvested with clear white stems, slightly bulbed, and with good strong green tops from a commercial operation on the Orleans Island, Quebec, Canada, during the summer season (i.e., July). Promptly after harvest, fresh green onions were trimmed and stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 95–98% relative humidity.

Visual quality of green onions declines quickly during storage, mainly due to leaf deterioration. Yellowing, wilting, curvature, and inner leaf elongation are the most evident signs of quality deterioration and are greatly influenced by storage temperature. The white immature bulb usually deteriorates slower than the leaves. 'Southport White Globe' green onions stored at 0°C maintain acceptable visual quality during 8 days (Figure 8.6). After 2 days, leaf elongation is already perceptible and increases throughout storage. After 6 days, yellowing is slightly noticeable in one of the outer leaves, which becomes completely yellowish and wilted after 12 days. After 14 days, all the leaves appear wilted and deteriorated, while the visual quality of the white immature bulb remains acceptable.

'Southport White Globe' green onions maintain acceptable visual quality when stored for 4 days at 5°C, yet leaf curvature and elongation becomes noticeable after 2 days (Figure 8.7). On day 4, a slight yellowish discoloration is already perceptible in one of the leaves, which becomes completely brownish-yellow and wilted after 12 days, whereas the remaining leaves appear wilted and dull green. After 10 days, the roots attached to the base of the immature onion bulb appear less turgid than at harvest.

Although green onions maintain acceptable visual quality during 3 days of storage at 10°C, leaf curvature is already noticeable at this time (Figure 8.8). After 5 days, leaf yellowing becomes apparent, and after 7 days leaf elongation is evident. After 11 days most of the leaves appear wilted, dry, and yellowish-green in color. The remaining roots attached to the immature bulb become wilted after 9 days.

Yellowing of the outer leaves becomes evident after 2 days in 'Southport White Globe' green onions stored at 15°C, and after 4 days the outer leaf is completely deteriorated (Figure 8.9). After 7 days the leaves are completely wilted, dry, and yellowish, while the roots that remained attached to the immature bulb appear wilted and less turgid than at harvest.

Deterioration of green onions stored at 20°C is extremely quick, and after only 1 day the outer leaf is already yellowish and slightly wilted (Figure 8.10). After 5 days the outer leaf is completely deteriorated, and after 7 days all the leaves are wilted and yellowish, while the roots appear dry.

Overall, 'Southport White Globe' green onions maintain better visual quality for longer periods of time when stored at 0°C (8 days) compared to storage at higher temperatures. Visual quality of green onions stored at 5, 10, 15, and 20°C deteriorates very quickly, becoming unacceptable after 4, 3, 2, and 1 day, respectively.

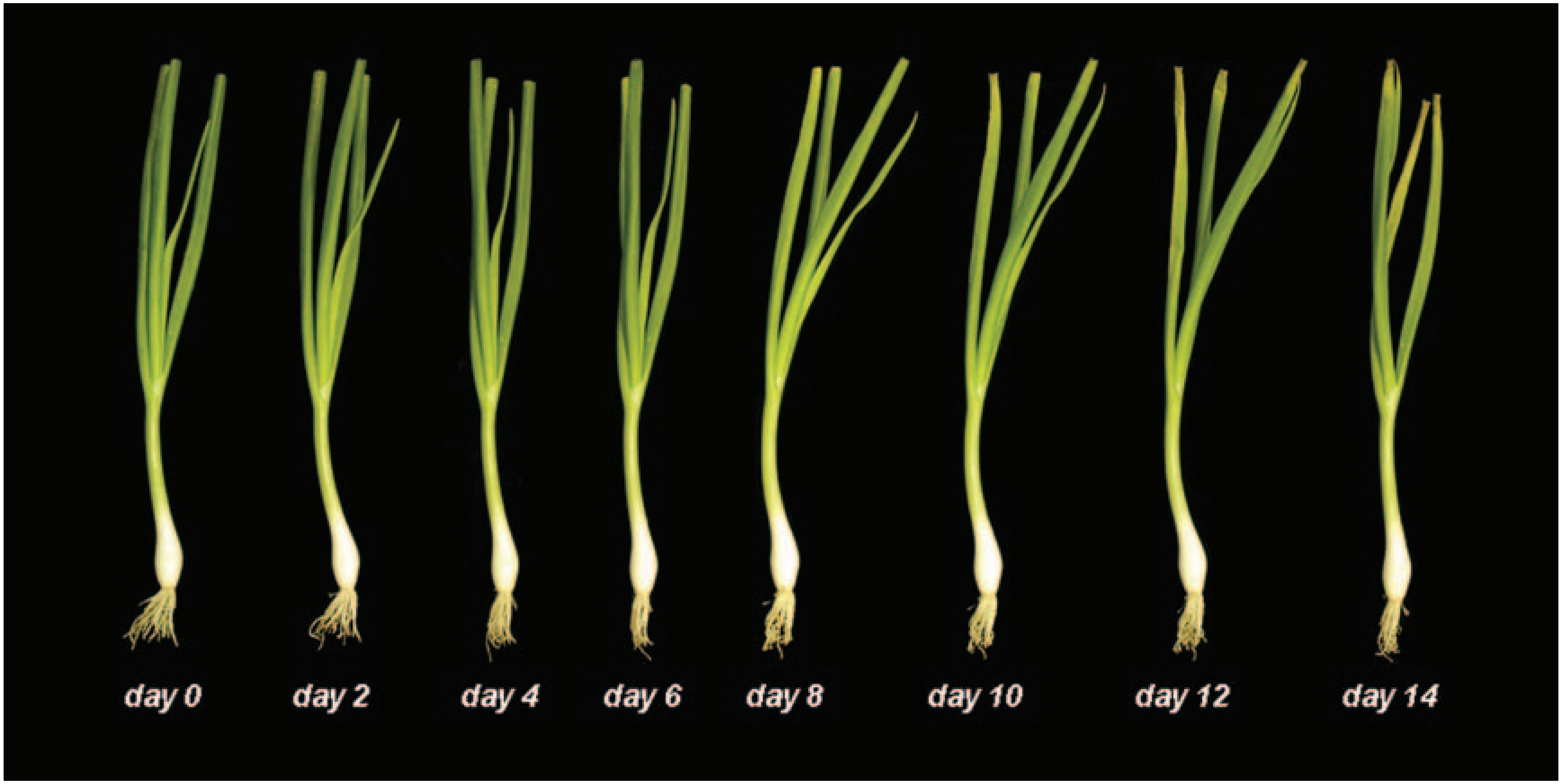
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Figure 8.6. Appearance of 'Southport White Globe' green onions stored for 14 days at 0°C. Green onions maintain acceptable visual quality during 8 days. Leaf elongation and yellowing are evident after 8 days.

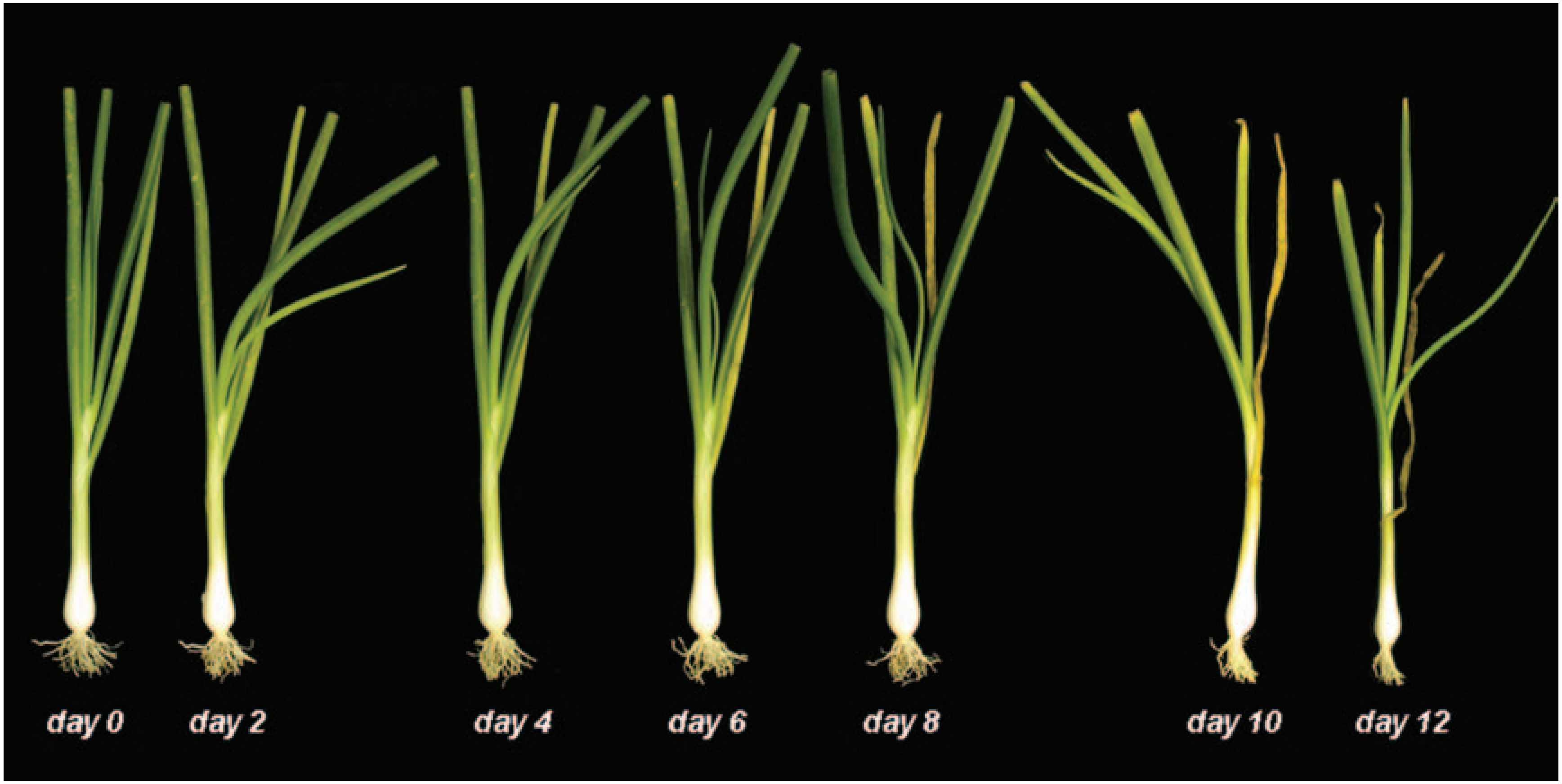
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Figure 8.7. Appearance of ‘Southport White Globe’ green onions stored for 12 days at 5°C. Green onions maintain acceptable visual quality during 4 days. On day 6 yellowing and leaf elongation are evident.

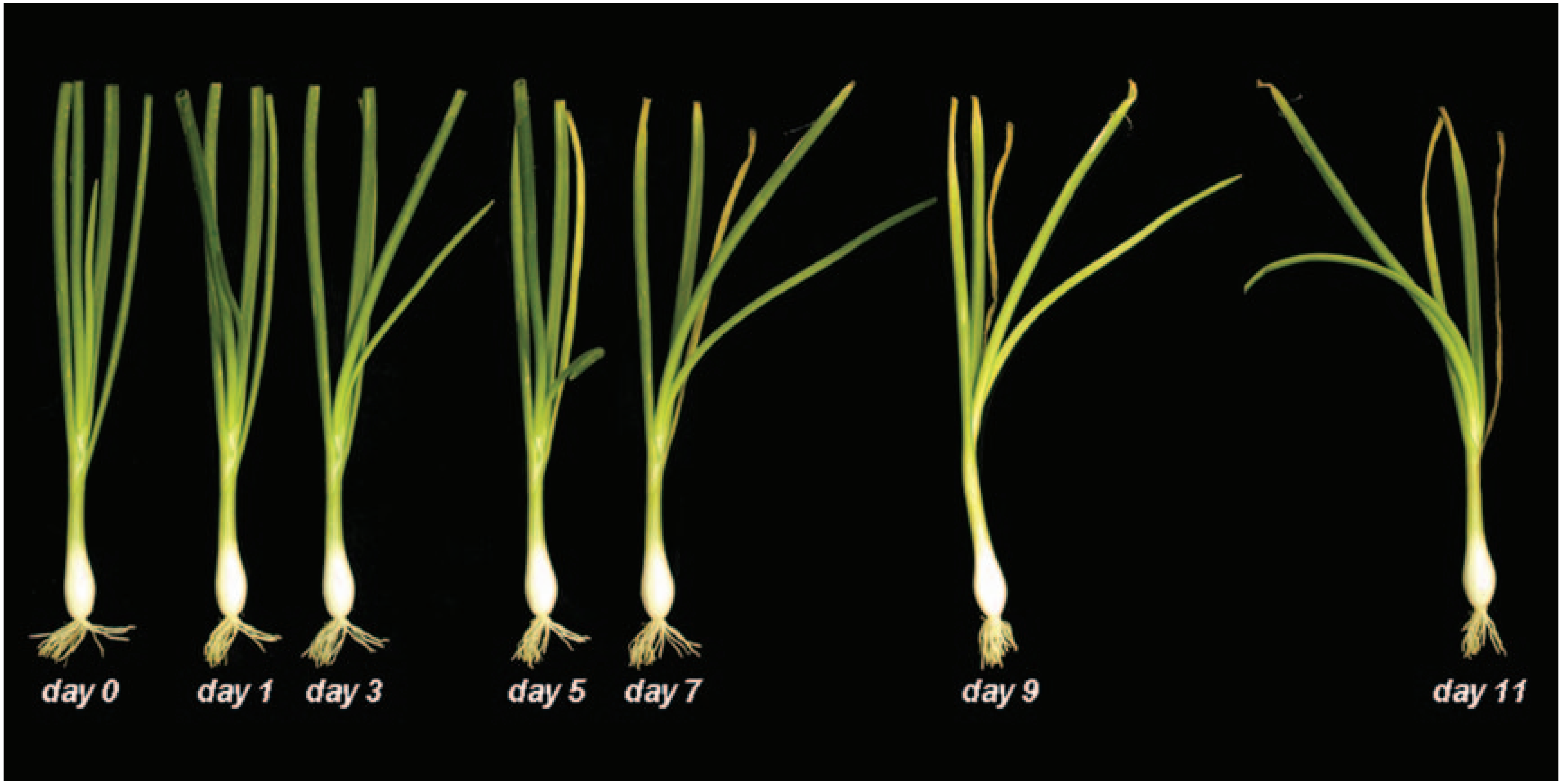
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Figure 8.8. Appearance of ‘Southport White Globe’ green onions stored for 11 days at 10°C. Green onions maintain acceptable visual quality during 3 days. After 5 days yellowing and leaf elongation are evident.

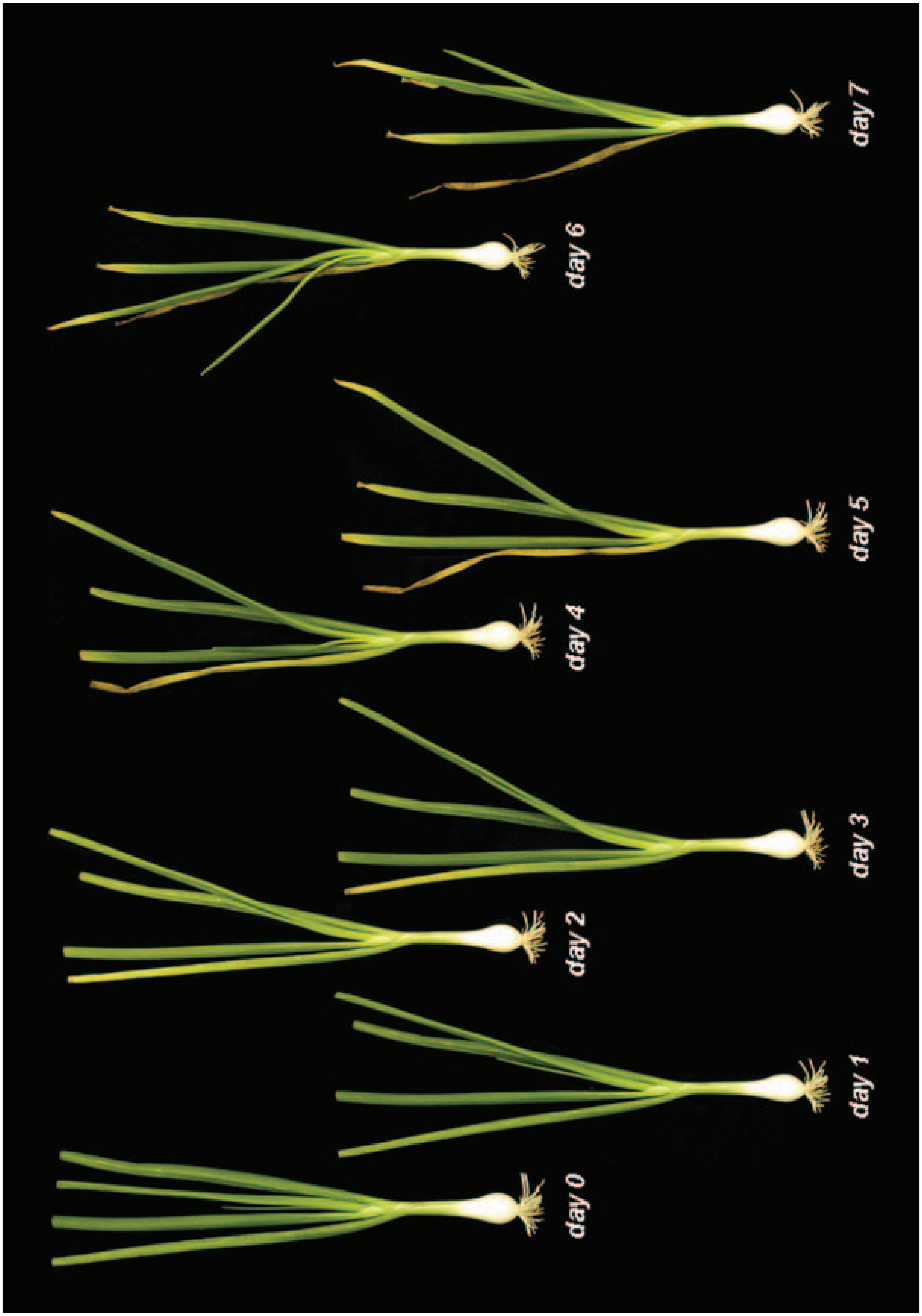
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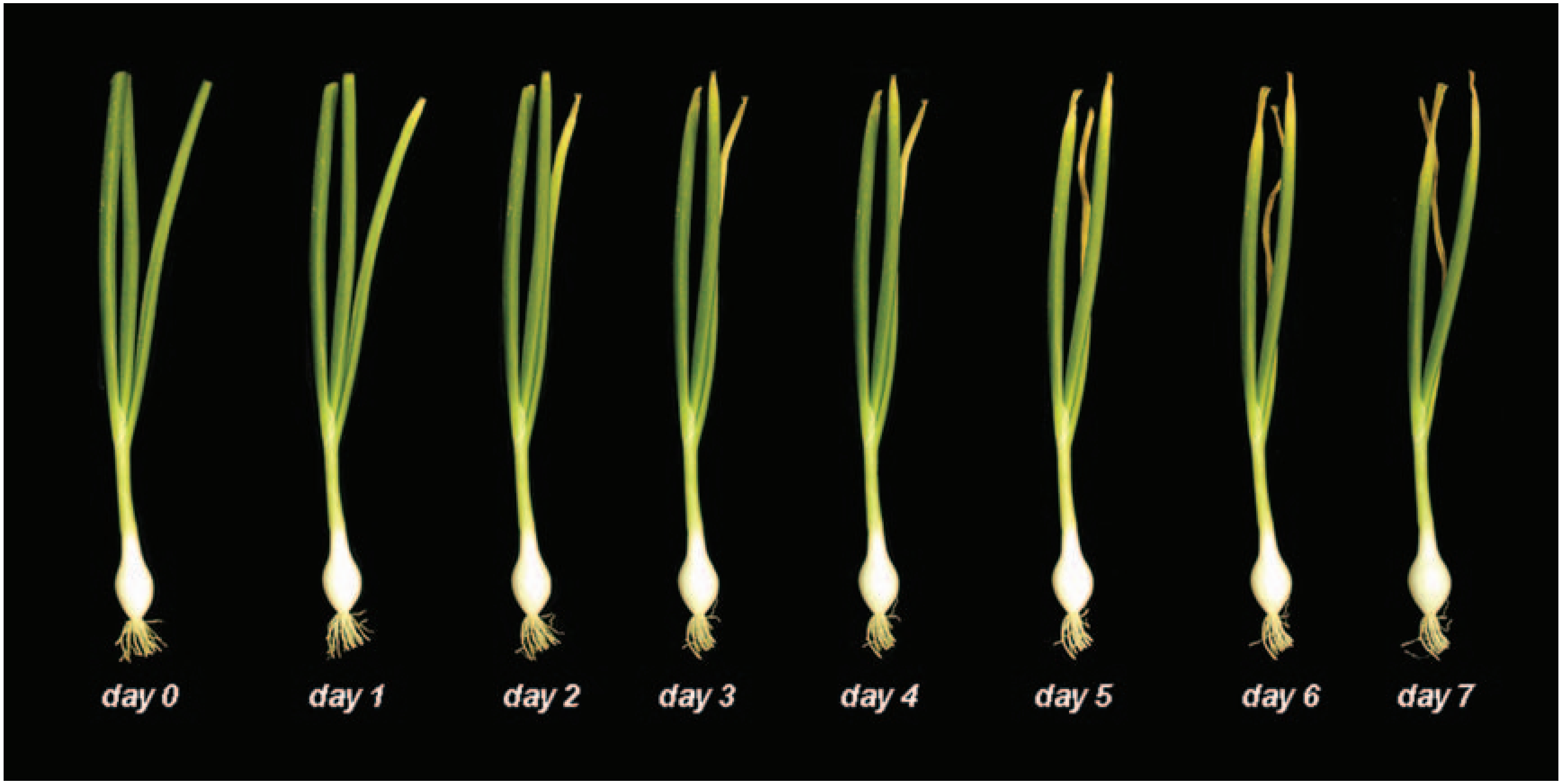
Figure 8.9. Appearance of 'Southport White Globe' green onions stored for 7 days at 15°C. Green onions maintain acceptable visual quality during 2 days. After 2 days, wilting, yellowing, and leaf elongation are evident.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day 1
day 2
day 3
day 4
day 5
day 6
day 7

Figure 8.10. Appearance of 'Southport White Globe' green onions stored for 7 days at 20°C. On day 1 yellowing of the leaves is already noticeable.

FRESH GARLIC

Scientific Name: *Allium sativum* L.
Family: Alliaceae

Quality Characteristics

Garlic has been cultivated since ancient times for its particular pungent flavor and medicinal properties. Although garlic's origin is uncertain, some consider the Mediterranean region as the original habitat, while others believe that it originated from southwestern Siberia or Central Asia. Garlic is grown nowadays in many countries, with China, India, Egypt, Spain, South Korea, and Turkey being the main producers (Etoh and Simon 2002; Fenwick and Hanley 1985).

Depending on the origin, different types of garlic plants may be found worldwide. Garlic plants are accordingly classified into three major groups: flowering plants without bulbils in the inflorescences, flowering plants with both flowers and bulbils in the inflorescences, and plants that form no flower stalks (Etoh and Simon 2002; Takagi 1990). Garlic cultivars may also be distinguished by the bolting type, number and size of primary and secondary cloves, bulb weight, taste of the cloves, color of the outer protective leaf of the cloves, number of protective leaves, width and length of the leaves, plant height, and tenderness of the green leaves (Takagi 1990). Garlic is also commonly classified into topset (hardneck) and softneck cultivars. Topset grows leafy tissue and later a flower stalk called a scape that emerges from the top of the plant. The lower part of the scape fills the inner part of the garlic bulb, preventing the development of interior cloves. This type of garlic produces on average eight to ten large outer cloves. Softneck garlic cultivars produce only leaves above the ground and do not produce scape or topset. Therefore, small cloves fill the internal part of the bulb and are surrounded by outer larger cloves (Kline 1990).

High-quality garlic bulbs should be firm to the touch and heavy for their size, clean, white, or with a color typical of the variety, well cured with dry neck and outer leaf sheaths. Cloves from mature bulbs should have a high dry weight and soluble solids content above 35% (Cantwell 2004). Light bulbs are undesirable, as they may be dry or decayed, while sprouting or root growth is also an undesirable visual quality factor (Ryall and Lipton 1979).

Garlic has a unique flavor and the particularity of improving the flavor of other foods, and therefore it is often used for culinary purposes. While intact garlic cloves have almost no odor or a light odor, once damaged the enzyme allinase is released from the disrupted cells and hydrolyses the S-alk(en)yl-L-cysteine sulfoxides to produce many sulfur volatile compounds associated with the characteristic garlic flavor and pungency (Lancaster and Boland 1990; Randle and Lancaster 2002). The main compound formed by this reaction is a thiosulfate, allicin, formed enzymatically from its precursor alliin; it is responsible for the characteristic odor and flavor of fresh garlic (Cantwell 2004).

In addition, regular consumption of garlic has been associated with several health benefits due to its high antioxidant capacity (Ackermann et al. 2001; Amagase et al. 2001; Benkeblia 2005; Bianchini and Vainio 2001; Fleischauer and Arab 2001; Prasad et al. 1995; Yin and Cheng 1998). Garlic is, in fact, a relatively rich source of total phenolics (15 µmol/g fresh weight), thiosulphinates (14.3–42.2 µmol/g fresh weight), namely allicin (13–89 µmol/g fresh weight), which may comprise more than 95% of all thiosulfinates present in garlic, and cysteine sulfoxides (11.75 mg/g fresh weight) (Baghalian et al. 2005; Benkeblia 2005; Block et al. 1992; Freeman 1975; Kaur and Kapoor 2002; Prasad et al. 1995; Vinson et al. 1998; Yin and Cheng 1998; Yoo and Pike 1998).

Garlic contains on average 59–78% water, 6% protein, 0.5 lipids, 33% carbohydrates, 2% fiber, and 1% sugars. Garlic is also a good source of minerals, vitamin C (31 mg/100 g fresh weight), and other vitamins in lower amounts (USDA 2006).

Optimum Postharvest Handling Conditions

Garlic intended for the fresh market may be harvested at an earlier stage, when the leaves of the plants begin to turn from green to yellow and the tips and margins of the leaves are brown and dry (Kline 1990). Care must be taken when harvesting, as in general, immature-harvested bulbs have a shorter postharvest life than those harvested completely mature (Nuevo and Bautista 2001; Oliveira et al. 2004). After harvest, the garlic bulbs are usually cured in order to reduce moisture (5–15% reduction in the initial bulb weight) (Kline 1990). There are several curing techniques. In some cases the bulbs are left in the field for several days until the leaves are completely dry; in other cases they are cured in a shaded and well-ventilated storage environment with a temperature between 15 and 30°C and a humidity level of 60–70% (Fenwick and Hanley 1985; Kline 1990). Curing will result in drying, shriveling, and sealing of the garlic necks, increasing the resistance of the bulbs from pathogen invasion and premature decay. Before storage the tops are trimmed to about 2.5 cm above the bulb (Kline 1990). After curing, garlic should be immediately stored at −1°C to 0°C if intended for prolonged storage (6–7 months), or at 20–32°C if intended for short-term storage (no more than 1–2 months). Relative humidity should be maintained between 60 and 70% at either high or low temperatures. Temperatures between 5 and 18°C or above 20°C are not recommended to store garlic, as they may accelerate sprouting and clove desiccation, while high humidity levels may result in mold growth and decay (Brewster and Rabinowitch 1990; Ryall and Lipton 1979). Decay may also be a problem if garlic was not well cured before storage (Cantwell 2004). In summary, optimum handling conditions for garlic are 8–10 days drying at 20–30°C (curing), followed by temperature reduction to 0°C and maintenance at −1–0°C with 60–70% relative humidity. Under such conditions expected postharvest life is 130–220 days, depending on cultivar (Cantwell 2004; Fenwick and Hanley 1985).

Temperature Effects on Quality

Garlic is considered a low perishable vegetable, and if handled under proper conditions its postharvest life may be as long as 7–9 months. However, when stored at temperatures above the recommended, loss of moisture may be significantly increased, resulting in dry, soft, and empty cloves; dormancy of the cloves may be prematurely terminated resulting in sprouting, and if garlic bulbs are stored at high temperature combined with high humidity levels, decay may also develop (Bertolino and Tian 1996; El-Oksh et al. 1971; Ragheb 1972; Vásquez-Barrios et al. 2006).

Loss of dormancy, and consequent sprouting, is one of the factors that may reduce the quality and marketability of stored garlic. Temperatures in the range of 5–18°C have been reported to prematurely break dormancy and induce sprouting of garlic cloves (Cantwell 2004). In fact, while there were no significant changes in the internal growth of the sprout during 100 days of storage at 0°C, indicating that the garlic bulbs were still dormant, at 5, 18, and 20°C, the dormancy period was shortened to 20–30 days (Vásquez-Barrios et al. 2006). Sprouting was also observed after 106 days in garlic stored either at 0°C and 90–95% humidity or at room temperature (15–30°C and 60–75% relative humidity); however, cloves stored at 0°C showed thinner sprouts than those stored at room temperature (El-Oksh et al. 1971). After 2 months at 19°C and 42% relative humidity, garlic sprouts began to grow, showing a significant increase between 60 and 180 days, exceeding 100% after 180 days of storage (Pérez et al. 2007).

Weight loss increases during storage of garlic, regardless of the storage temperature. However, the percentage of weight loss in garlic stored at room temperature (15–30°C and 60–75% relative humidity) was much higher (62%) than that of garlic stored at 0°C and 90–95% relative humidity (27%) after 289 days of storage. After 289 days, garlic stored at room temperature was completely dry, while after 321 days garlic stored at 0°C was attacked by decay (El-Oksh et al. 1971). Garlic bulbs (cv. Perla) stored at 0°C and 84% relative humidity and at 0°C and 70% relative humidity showed a weight loss of 3.6 and 5%, respectively, after 190 days of storage, while bulbs stored at 5°C (74% relative humidity), room temperature (18°C, no humidity control), 20°C (55% relative humidity), and 30°C (46% relative humidity) lost about 33, 24, 19, and 16% of their initial weight, respectively, after the same period of time. After 160 days, the bulbs stored at 5°C showed the highest weight loss compared to garlic stored at higher or lower temperatures, and after 90 days decay also developed in garlic stored at 5°C but not in that stored at room temperature, 20 or 30°C (Vásquez-Barrios et al. 2006).

An apparent relationship was observed between internal sprouting and weight loss. That is, the weight loss was somewhat low (3.5%) while the sprout did not exceed the length of the clove, but increased very quickly (9–11%) when the sprout became longer than the clove (Vásquez-Barrios et al. 2006). Therefore, a maximum weight loss of 3.5% and a maximum internal sprout growth of 50% were proposed as a shelf life limit for stored garlic. Accordingly, storage at 0°C resulted in longer shelf life of 150–160 days, while storage at 5, 18, and 20°C reduced the shelf life of garlic to about 60–80 days. Maximum shelf life of garlic stored at 30°C was 100 days (Vásquez-Barrios et al. 2006).

Postharvest treatments, such as heat or irradiation, applied to garlic cloves prior to long-term storage have successfully reduced sprouting (Cantwell et al. 2003; Ceci et al. 1991; Curzio and Urioste 1994; Curzio et al. 1986; El-Oksh et al. 1971; Pérez et al. 2007). For example, hot-water treatments of 60°C for 2.5 minutes and 55°C for 10 minutes controlled sprout growth in garlic cloves stored at 10°C and 95% relative humidity, without reducing the thiosulfinate content and garlic pungency or inducing change in color and firmness. Hot-water-treated garlic cloves stored at 0–1°C and 65–75% relative humidity remained sprout free for 6 months (Cantwell et al. 2003).

Compared to nonirradiated garlic cloves, irradiated garlic bulbs held at 0°C and 90–95% relative humidity lost less weight, showed less sprouting and empty cloves, and remained in good condition during 370 days (El-Oksh et al. 1971), while pyruvate content was not significantly affected (Curzio et al. 1986). Similarly, irradiated garlic stored for 240 days at 19°C and 42% relative humidity showed a significantly lower percentage of sprout growth than nonirradiated garlic (Pérez et al. 2007). Irradiation applied to garlic did not affect the firmness, flavor, or odor of the cloves (Ceci et al. 1991; Curzio and Urioste 1994).

Softening of garlic cloves during storage is mostly caused by excessive loss of moisture during storage and is affected by clove maturity at harvest and also by storage time and temperature. A rapid increase in softening was observed in immature, poorly cured garlic bulbs during storage for 180 days at 29°C, while more mature bulbs were still firm after the same period of time (Nuevo and Bautista 2001). Firmness of 'Perla' garlic cloves also decreased during storage and was influenced by the storage temperature. Garlic stored at 0°C maintained its initial firmness after 190 days of storage, whereas firmness of garlic stored at 5°C was significantly reduced after the same period of time. Garlic stored at 18, 20, and 30°C showed firmness values between those of garlic stored at 0°C and at 5°C (Vásquez-Barrios et al. 2006).

Soluble solids content of 'Perla' garlic stored at 5°C declined significantly during storage from initial values of 36-31% after 190 days of storage (Vásquez-Barrios et al. 2006). In garlic bulbs stored at 29°C, initial soluble solids content increased after 30 days of storage and then decreased from values of about 19 and 20% to 8% after 60 days (Nuevo and Bautista 2001). Also, ascorbic acid content of garlic stored under warehouse conditions was reduced from initial values of about 48 mg/100 g to about 33 mg/100 g dry weight after 270 days of storage (Curzio et al. 1986).

Alliin content of garlic tends to change during storage; however, there is no agreement in the way the concentration of this compound changes. Some authors report a decrease in alliin content of garlic during storage (Cantwell 2004), while others report significant increases (Ichikawa et al. 2006) or no changes during cold storage (Hughes et al. 2006). On the other hand, isoalliin content significantly increased, while concentration of other sulfur-containing compounds decreased during cold storage (Hughes et al. 2006; Ichikawa et al. 2006). After 150 days at 4°C, a 39% decrease was observed in the concentration of sulfur-containing compounds of garlic cloves, whereas only slight decreases were observed in these compounds in garlic stored at 23°C (Ichikawa et al. 2006). Although an increase in sulfur-containing compounds and pyruvate was observed in garlic stored under warehouse conditions (6–32°C and 58–86% relative humidity) after 180 days of storage, both sulfur-containing compounds and pyruvate contents significantly decreased henceforward until the end of storage (Ceci et al. 1991). Similarly, in garlic stored at 29°C, pyruvate content increased during 90 days of storage and decreased afterward (Nuevo and Bautista 2001). Pyruvate content of garlic stored under warehouse conditions also decreased during storage from initial values of 240 μmoles/g to about 216 μmoles/g of dry weight after 270 days of storage (Curzio et al. 1986). Conversely, diallyl disulfide, the major sulfide in macerated 'Red' garlic bulbs, significantly increased during storage (Ceci et al. 1991). It was suggested that during cold storage of garlic, sulfur-containing compounds are converted to sulfoxides such as alliin and isoallin (Hughes et al. 2006; Ichikawa et al. 2006).

Time and Temperature Effects on the Visual Quality of 'Music' Garlic

'Music' garlic shown in Figures 8.11–8.16 was harvested at the mature stage with half or slightly more than half of the leaves showing green color and with green stalk, from a commercial operation on the Orleans Island, Quebec, Canada, during the summer season (i.e., July). Promptly after harvest, fresh noncured garlic was stored at five different temperatures (0.5 ± 0.5°C, 5.0 ± 0.2°C, 10.0 ± 0.4°C, 15.0 ± 0.2°C, and 20.0 ± 0.2°C) and with 80–85% relative humidity.

Major visual quality changes observed in 'Music' fresh noncured garlic during storage at different temperatures include discoloration of the external skin, yellowing of the green stalk, dryness of the cloves with separation from the lower part of the scape, and slight internal sprout growth (emergence of whitish sprout leaves). Compared to the postharvest life of cured garlic reported in the literature, noncured garlic shows a decline in the visual quality much faster, and consequently shorter postharvest life, particularly when stored at temperatures higher than 0°C. High relative humidity (80–85%) during storage may have also contributed to increase in the development of decay in garlic bulbs stored at 20°C. Thus, 'Music' garlic stored at 0°C maintains acceptable external visual quality during 18 days, with only minor yellowing of the green stalk after 16 days (Figure 8.11). A slight discoloration of the external skin of the bulb is also perceptible after 16 days of storage. Internal sprout growth is very subtle, with a whitish sprout leaf becoming apparent after 12 days. Clove separation from the lower part of the scape is evident after 10 days. After 18 days, the cloves separate from the lower part of the scape, which appears drier than at harvest.

Fresh noncured garlic stored at 5°C maintains acceptable external visual quality during 12 days, after which the skin of the garlic bulb becomes slightly discolored and the green stalk turns yellowish-green (Figure 8.12). Internal sprout growth becomes apparent after 12 days, with a whitish sprout leaf becoming apparent at this time. After 16 days the cloves separate from the lower part of the scape, which appears less turgid than at harvest.

'Music' fresh garlic stored at 10°C maintains acceptable quality during 5 days (Figure 8.13). Discoloration of bulb skin, emergence of a whitish sprout leaf, and clove separation from the base of the scape become evident after 5 days. After 8 days, the base of the scape where the roots were originally attached becomes dry and brownish.

Emergence of the whitish sprout leaves is very quick when noncured garlic is stored at 15°C (Figure 8.14). After only 2 days the internal whitish sprout leaves are evident in both cloves, while bulb external skin discoloration becomes apparent after 3 days. After 6 days, the bulb skin color darkens and becomes less white than at harvest, while the cloves appear completely separated from the base of the scape, which appears more dry than at harvest.

‘Music’ noncured garlic stored at 20°C maintains acceptable visual quality during 2 days (Figure 8.15). After 2 days the external skin of the bulb appears less white than at harvest and the stalk less green. The cloves start to separate from the base part of the scape after 2 days and are completely separated after 4 days. After 4 days the scape appears dry and the base slightly brownish, while empty cavities develop inside the cloves.

Figure 8.16 shows temperature-related disorders in fresh noncured ‘Music’ garlic during storage at temperatures higher than 5°C. Emergence of the internal leaves (sprouting) is evident in some garlic cloves after 7 days at 10°C, and dryness of the external skin of the bulb with exposure of the garlic cloves is also noticeable in some bulbs after 5 days at 10°C and after 3 days at 15°C, while mold develops in some of the garlic bulbs after 6–7 days at 15°C, and after 5 days at 20°C.

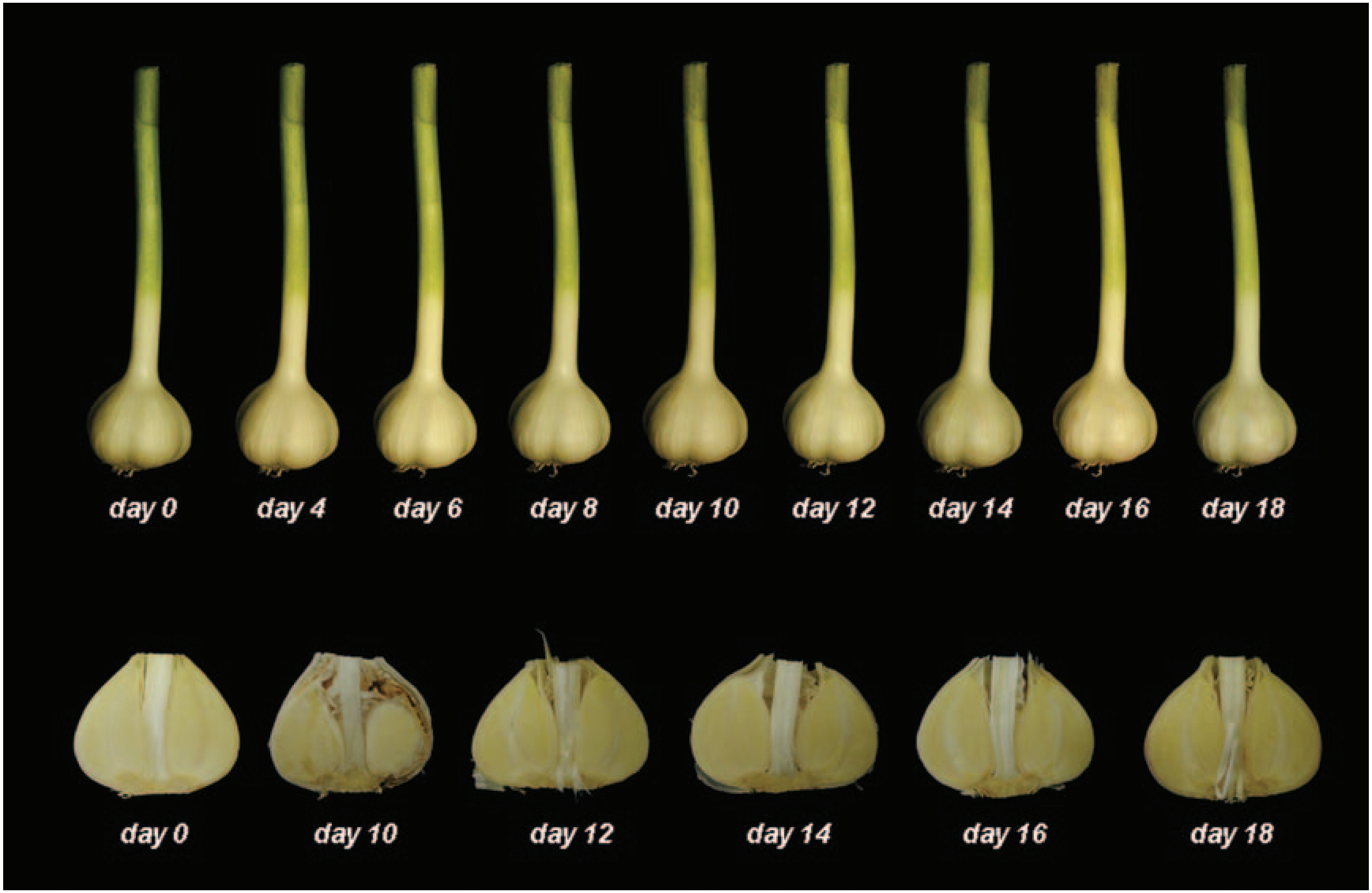
day 0
day 4
day 6
day 8
day 10
day 12
day 14
day 16
day 18
day 0
day 10
day 12
day 14
day 16
day 18

Figure 8.11. Appearance of fresh noncured 'Music' garlic stored for 18 days at 0°C. Fresh garlic maintains acceptable external visual quality during 16 days. After 10 days a subtle internal sprout growth is noticeable, while separation of the cloves from the lower part of the scape is evident.

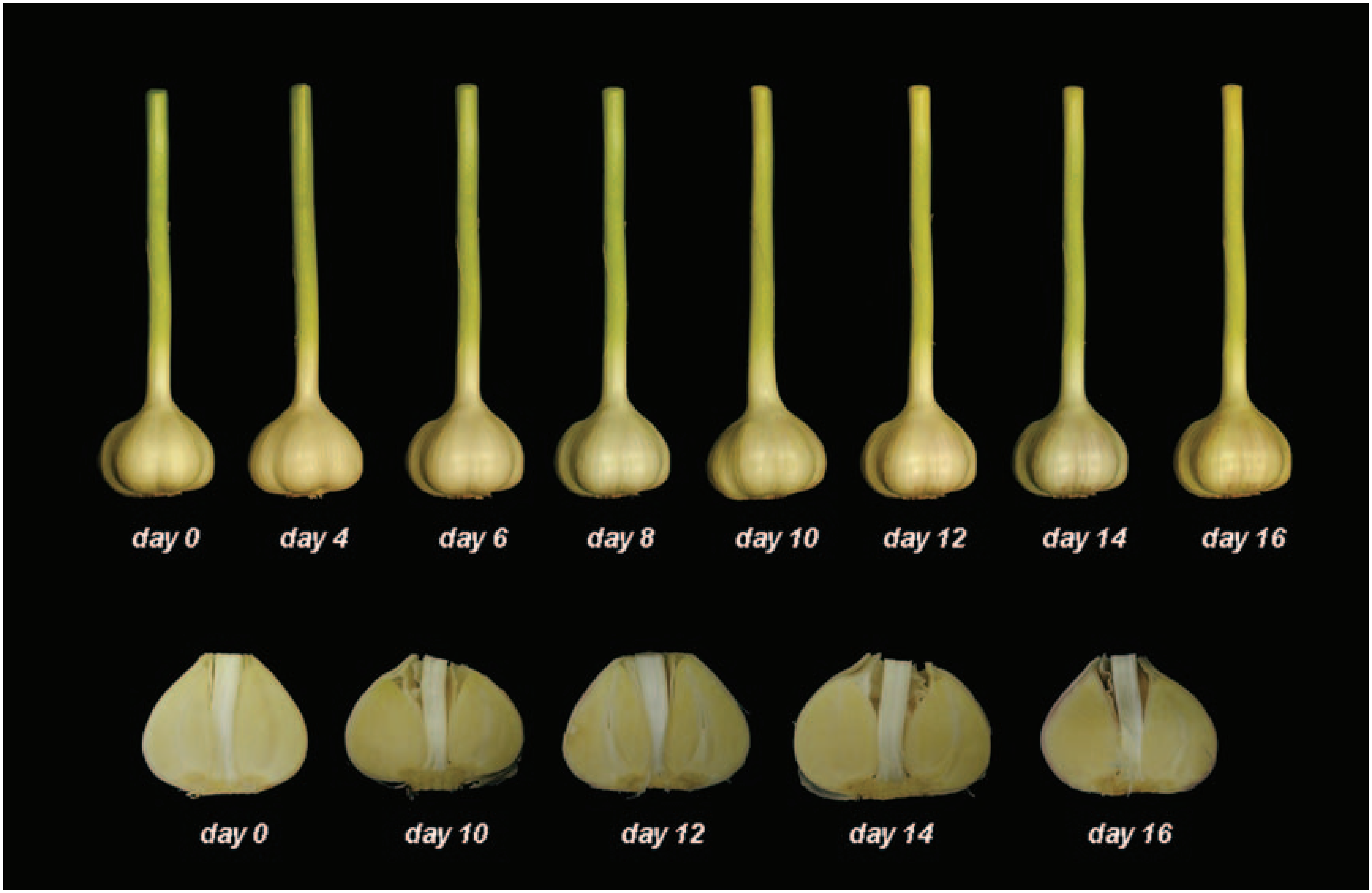
day 0
day 4
day 6
day 8
day 10
day 12
day 14
day 16
day 0
day 10
day 12
day 14
day 16

Figure 8.12. Appearance of fresh noncured 'Music' garlic stored for 16 days at 5°C. Fresh garlic maintains acceptable visual quality during 12 days. Whitish sprout leaf emergence is apparent after 12 days.

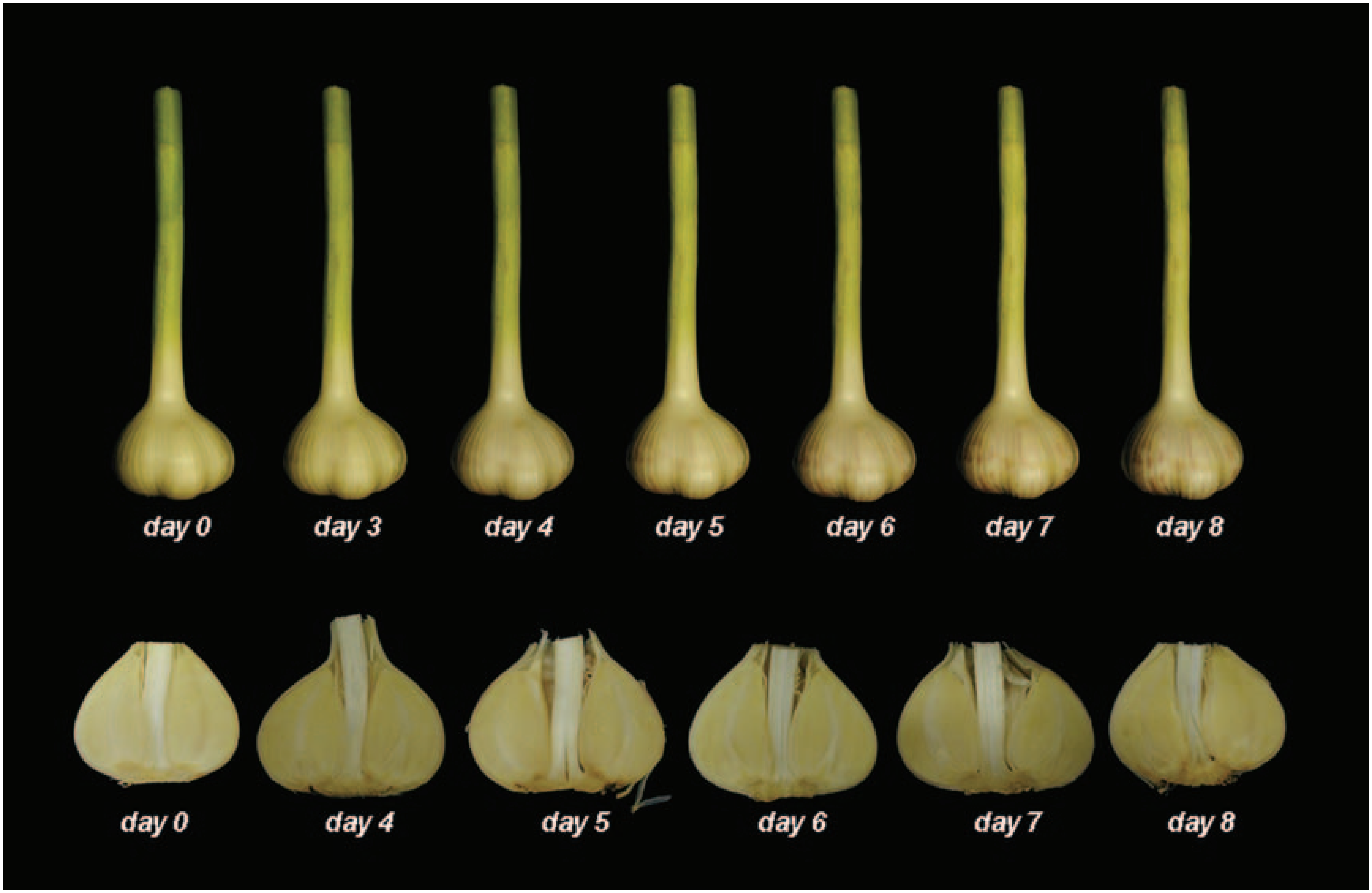
day 0
day 3
day 4
day 5
day 6
day 7
day 8
day 0
day 4
day 5
day 6
day 7
day 8

Figure 8.13. Appearance of fresh noncured 'Music' garlic stored for 8 days at 10°C. Fresh garlic maintains acceptable quality during 5 days. Discoloration of bulb skin, sprouting, and clove separation from the base of the scape become evident after 5 days.

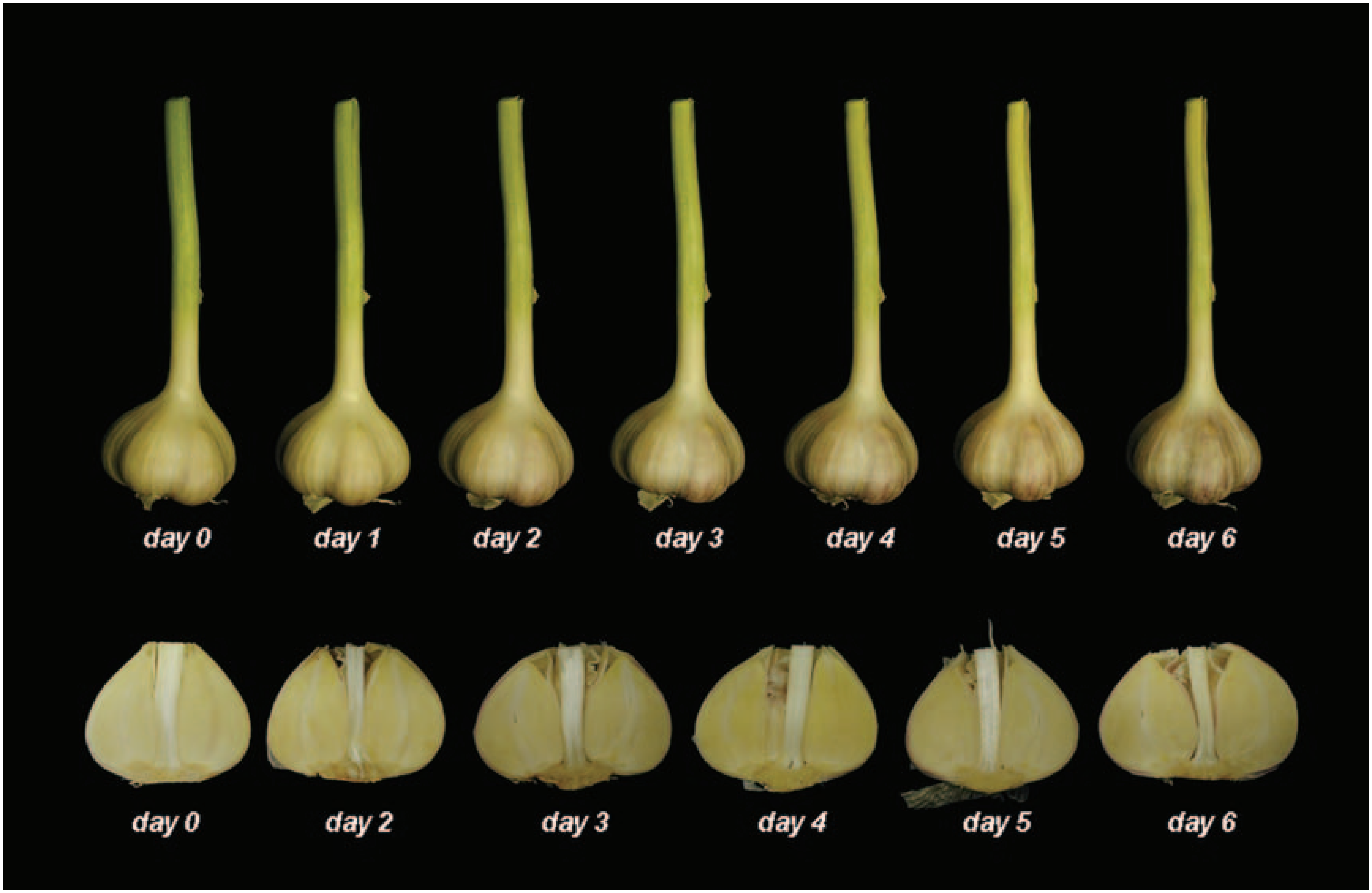
day 0
day 1
day 2
day 3
day 4
day 5
day 6
day 0
day 2
day 3
day 4
day 5
day 6

Figure 8.14. Appearance of fresh noncured 'Music' garlic stored for 6 days at 15°C. Fresh garlic maintains acceptable visual quality during 3 days.

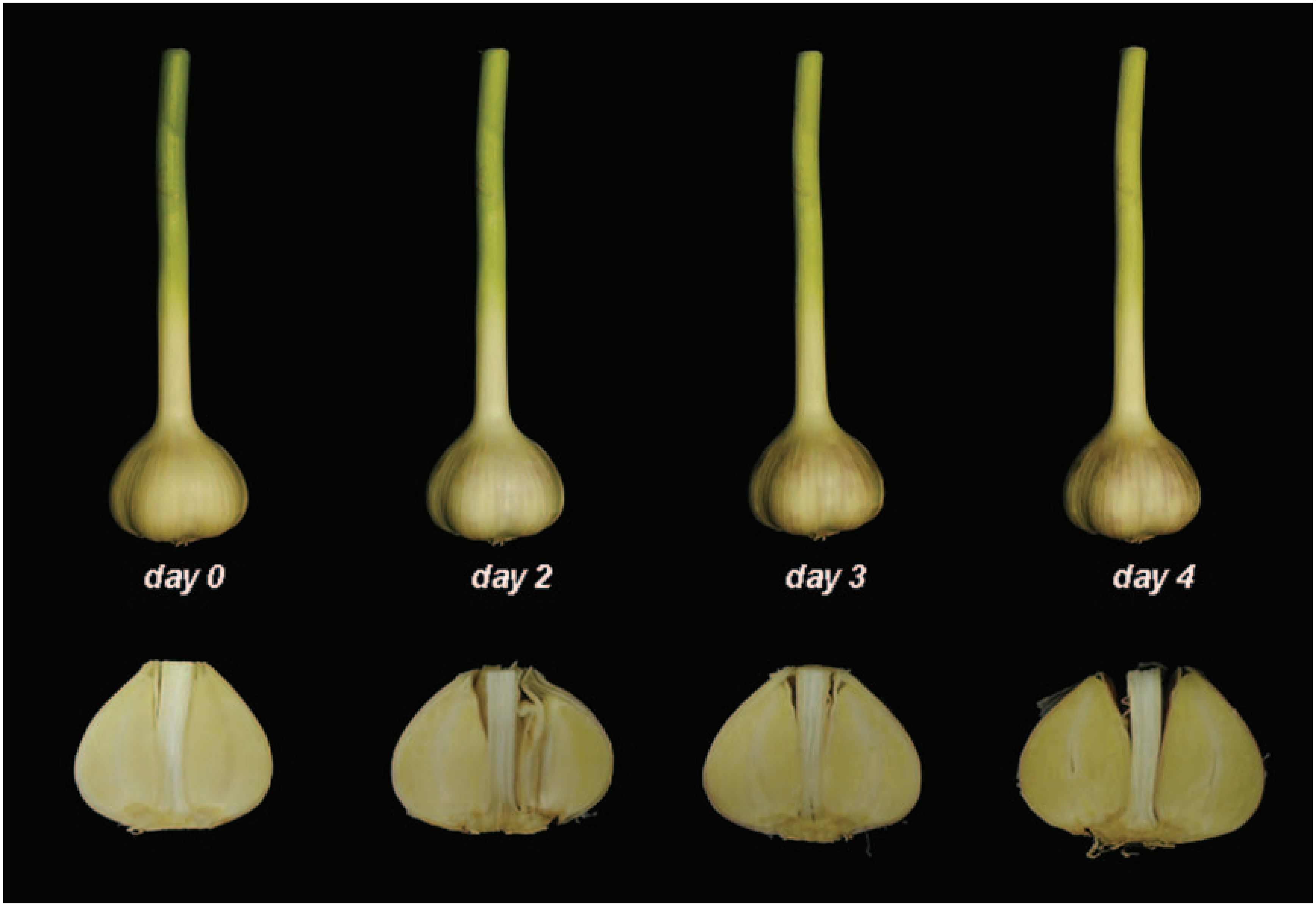
day 0
day 2
day 3
day 4

Figure 8.15. Appearance of fresh noncured 'Music' garlic stored for 4 days at 20°C. Fresh garlic maintains acceptable visual quality during 2 days.

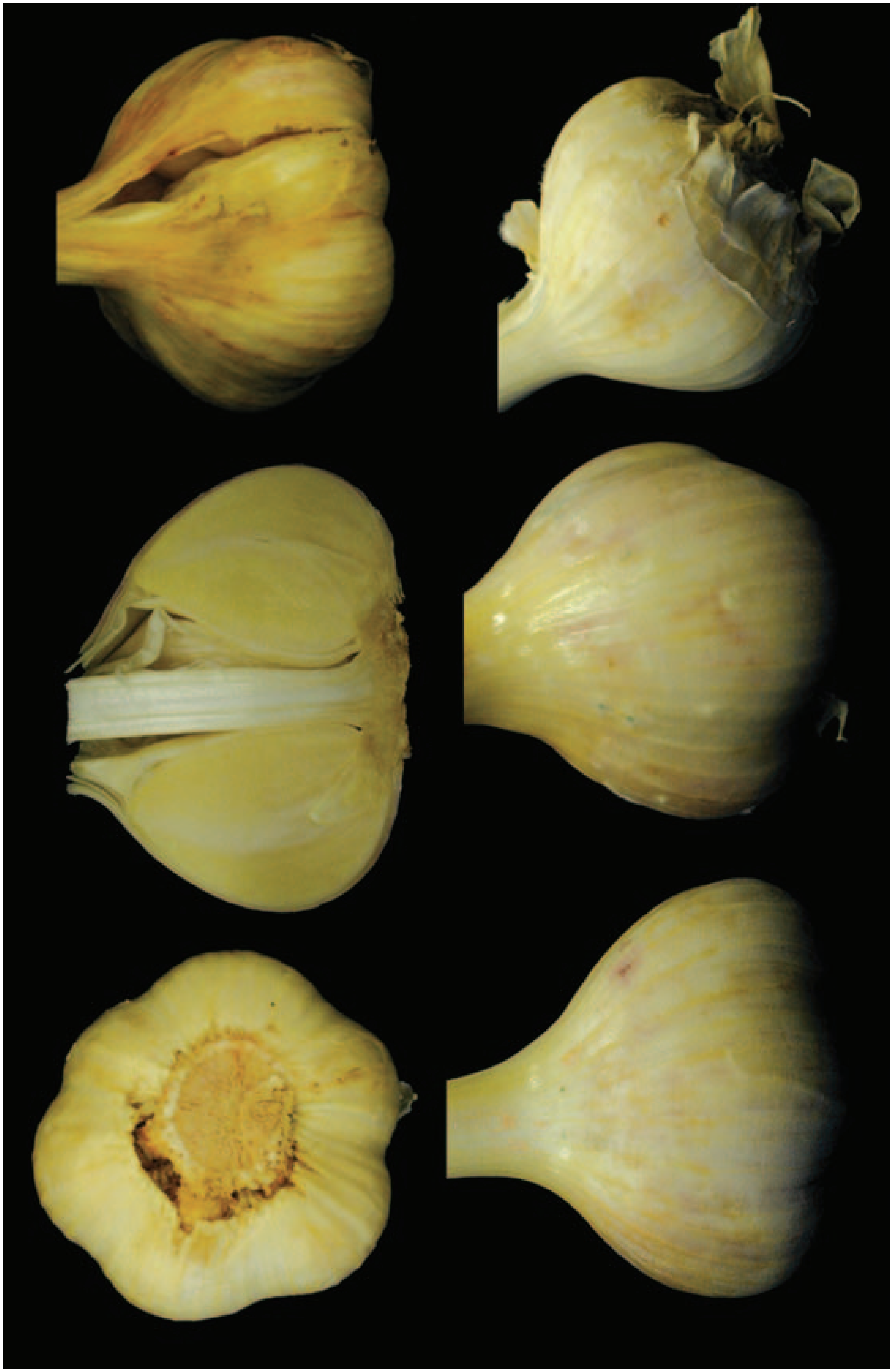

Figure 8.16. Storage disorders in fresh noncured 'Music' garlic. Dryness of the base of the scape and separation of the bulb external skin after 5 days at 10°C (above left); internal sprouting after 7 days at 10°C (above middle); browning and dryness of the external bulb skin with rupture and exposure of the garlic cloves after 3 days at 15°C (above right); decay of the external skin after 6 days at 15°C (below left); blue mold growth after 7 days at 15°C (below middle); white mycellim growth after 5 days at 20°C (below right).

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